An X-Band Monolithic Active Mixer in SiGe HBT Technology

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Abstract

We present the design, novel fabrication techniques, and measurements of a SiGe HBT X-Band active mixer MMIC. By implementing microstrip transmission lines on an inexpensive, low-loss spin-on dielectric above the lossy Si substrate, we use the high-speed SiGe HBTs in "classical" monolithic microwave circuits.

Introduction

Microwave mixers are integral components of most RADAR, telecommunication, and metrology systems. Mixers can be designed in the active (lower conversion loss, higher noise) or passive (higher conversion loss, lower noise) modes, as required by the application. At microwave frequencies, mixers can be realized as hybrids using discrete components bonded to a substrate containing the passive circuitry or as MMICs [1]. The cost of these components can be high since hybrids typically require manual assembly, and MMICs are large (compared to the area consumed by discrete components) and are fabricated on expensive substrates (e.g. GaAs).

Recently, $Si_{1-x}Ge_x$/Si HBT transistors have been developed which achieve cutoff frequencies to 50-120 GHz [2,3,4], approaching those of III-V HBTs. Unfortunately, utilization of these devices is difficult because a significant problem with Si based MMICs is the lack of a semi-insulating Si substrate. High resistivity silicon has been used [3]; however, these substrates are often more costly than the III-Vs and are not always compatible with typical Si production lines.

By using a low-cost, high-performance spin-on dielectric on top of the Si substrate [5], we developed a Si based MMIC mixer. This mixer achieves > 0 dB conversion gain from 8 to 11 GHz and is relatively insensitive to LO drive level variations. This technology offers the advantages of low-cost, high-yield SiGe HBTs with the flexibility of classical MMICs. The circuit presented here demonstrates the feasibility of SiGe MMICs; they can be scaled to higher frequencies and offer opportunity to incorporate much higher levels of integration (e.g. VCO, mixer, A/D converter on a single MMIC).

SiGe MMIC Technology

The epitaxial-base SiGe HBT technology utilized for this circuit is similar to that described in [2,6,7]. It employs 200 mm wafers,

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SiGe HBTs with f_T and f_{MAX} near 50 GHz, three levels of Al/Cu metalization, polysilicon resistors, low resistance substrate contacts, and bypass capacitors of 1.4 fF/μm². The high-frequency performance of the circuits is enhanced by deep and shallow trench isolation combined with the inherent speed advantages of the UHV/CVD insitu-boron-doped SiGe base region. Typical emitter depths are 25 nm, and typical base widths are 85 nm.

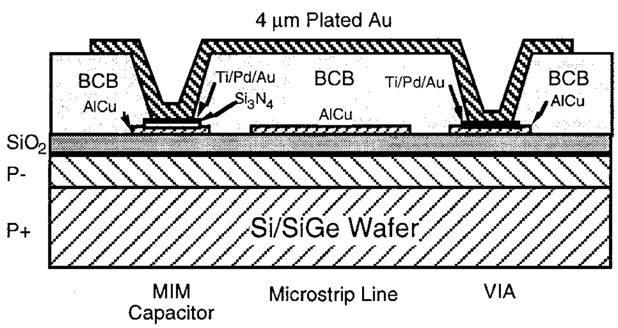

Figure 1. Cross sectional view of the BCB-based microwave element process. Standard Si-based processes include top-level AlCu metal and Si_3N_4 passivation. Adding a diffusion barrier prevents Al and Au contamination.

In order to fabricate passive microwave components such as microstrip lines and metal-insulator-metal (MIM) capacitors on top of the high-speed HBT wafers, we use a thick spin-on dielectric and plated Au interconnections [5]. Figure 1 shows a cross-sectional view of the Si-based MMIC. The ground plane (actually the top-level of the HBT metalization) consists of 0.8 μm of Al/Cu at 0.045 Ω/sq. capped by 2000 Å of Si_3N_4 (used to implement MIM capacitors). The Si_3N_4 is etched to provide vias between the Si-based devices and the microwave circuitry above. On top of this structure we deposit a diffusion barrier and spin on a 13 μm thick layer of benzocyclobutene (BCB), a high quality, low loss, thermally cross-linked polymer with a low dielectric constant [8]. After etching vias in the BCB, we electroplate Au traces that perform as standard microstrip circuitry and interconnect to the Si-based devices through vias and MIM capacitors. Figure 2 shows a comparison between 50 Ω transmission lines fabricated on Si, GaAs, and BCB. The loss of the 50 Ω BCB line is approximately twice that of a typical line on GaAs.

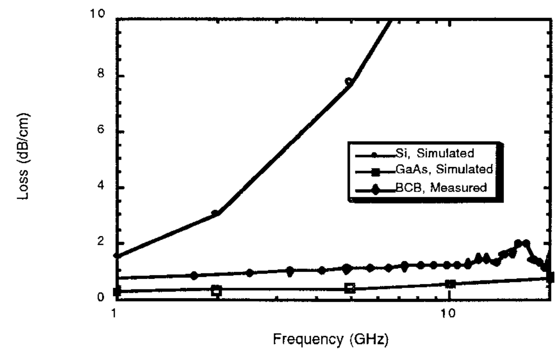

Figure 2. Normalized loss vs. frequency for 50 Ω transmission lines on Si, GaAs, and BCB. The BCB transmission line has twice the loss of one fabricated on GaAs, but less than 1/10 the loss of one fabricated on Si.

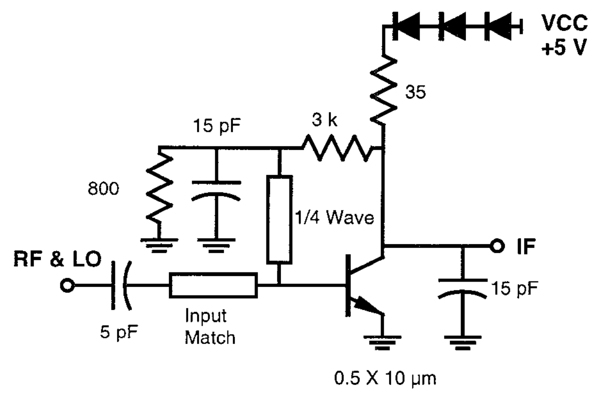

Figure 3. Schematic diagram of a single active mixer element.

Circuit Description

The singly balanced mixer consists of a rat-race hybrid and two individual single-device HBT mixers (Figure 3). A single 0.5 X 10 μm² HBT is used for each mixing element. The LO and RF are applied to the base, and the IF is filtered from the collector. The input circuit consists of a 5 pF DC blocking capacitor, a series-line matching circuit, and a DC bias network. This simple matching circuit provides a good impedance match, adequate bandwidth, and can be characterized accurately. The hybrid is a classical rat-race, realized with meandering lines to minimize chip area.

A 90° high-impedance line is used to provide base bias; the base is biased close to turn-on by the 3 kΩ and 800 Ω resistors in the base voltage divider. This minimizes the LO power required to pump the mixer and guarantees that the collector conduction duty cycle will be close to the optimum value of 50%.

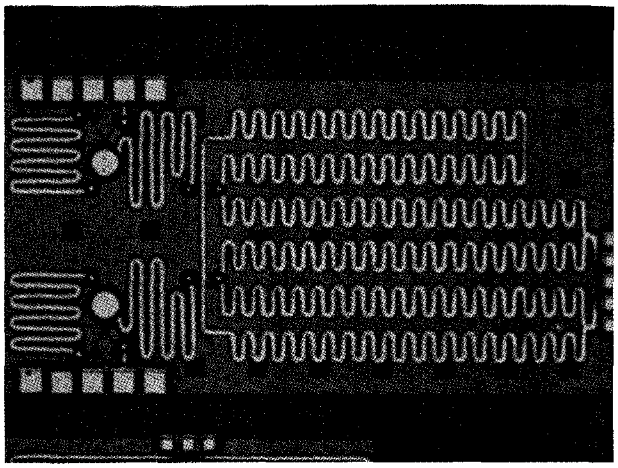

Figure 4. Photograph of entire singly-balanced active mixer (3.1 X 1.6 mm).

Because of the low output frequency (< 10 kHz), an IF matching circuit is not used, and the mixer is designed to provide voltage conversion gain (not necessarily power gain) since the IF load impedance is 2 kΩ. The collector circuit consists of a 35 Ω resistor and three diodes. The diodes reduce the DC supply by approximately 2 V and provide a current dependent load to the mixer. This helps level the conversion gain when DC current varies in response to changes in LO level. Of course, the diodes may introduce distortion; this is not a problem in this application, but may not be acceptable in others. A single 15 pF capacitor is used to bypass the LO and RF frequency components at the collector. A photograph of the complete MMIC mixer is shown in Figure 4.

Circuit Measurements

Measurements were made on-wafer using microwave probes. LO and RF signals were synthesized sources (hp 83640A), and the IF was measured as a differential signal by a sampling oscilloscope (tek CSA 801) driving a 2 kΩ load. The LO drive level was adjusted to remain constant over frequency at the input port on the MMIC, while the RF signal was maintained at -20 dBm, well within the linear range of the mixer (-1 dB compression occurs near 0 dBm RF level). Figure 5 shows the measured conversion gain vs. frequency for three LO drive levels at an IF frequency of 100 kHz. The conversion gain remains 1 ± 1 dB over the 8 to 11 GHz frequency range and over the 4 dB of LO power variation.

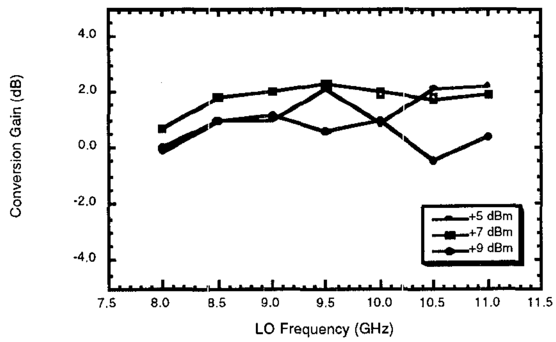

Figure 5. Measured conversion gain vs. frequency at three LO drive levels for a 100 kHz IF frequency.

Figure 6 shows the measured LO-to-RF isolation. This measurement was performed by terminating the IF lines and connecting the RF port to a power meter (hp 437B). The isolation increases to 25 dB at 11 GHz. This indicates that the rat-race hybrid was resonant at a higher frequency than the designed 10 GHz. The IF signal shows a 1 dB roll-off at 100 MHz governed by the 35 Ω output resistance and the 15 pF filter capacitor (3 dB should occur near 300 MHz).

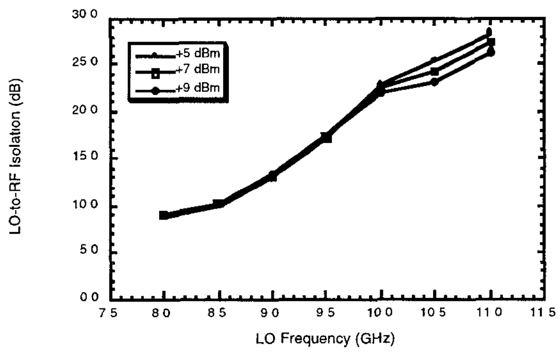

Figure 6. Measured LO-to-RF isolation vs. frequency at three LO drive levels.

Conclusions

Although mixers have been created with comparable performance in various technologies, the work presented here shows unique merit. The passive element process provides classical microwave circuits on standard Si substrates. Using this technique, high levels of integration are possible with the high performance, high yield SiGe HBTs. This allows one to include active IF filters, temperature compensation, analog-to-digital conversion, frequency division, a local oscillator, etc. on the same die as the mixer. Given the 3-dimensionality of the process, all circuitry not incorporating microwave elements can be fabricated under the rat-race hybrid (e.g. A/D converter, frequency divider), so as to not increase die area. The design can also be scaled to higher frequencies since the response of the circuit is governed by transmission lines. Offering these unique advantages, this new process reveals the potential for low cost MMIC mixers as well as other microwave components.

References

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