SiGe MMICs and Flip-Chip MICs for Low-Cost Microwave Systems

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Abstract

Recent Progress in SiGe device technology has improved cutoff frequencies of these devices to beyond 200 GHz. This work describes two approaches for implementing distributed structures with Si substrates: microstrip transmission lines using thick polyimide over a ground plane on the substrate (polyimide MMIC) and small Si devices or chips flip-chip mounted onto a microwave circuit board containing the distributed elements (flip-chip MIC). Microwave circuits such as amplifiers, oscillators, mixers, and frequency dividers have been demonstrated using both techniques.

Introduction

In order to fully utilize the performance of high-speed semiconductor devices, microwave components such as inductors, tuned matching networks, reactive loading, power splitters, etc. are required [1]. Monolithic microwave integrated circuits (MMICs) using distributed elements such as transmission lines for such components are commonly implemented on semi-insulating (SI) III-V compound semiconductor substrates (GaAs or InP).

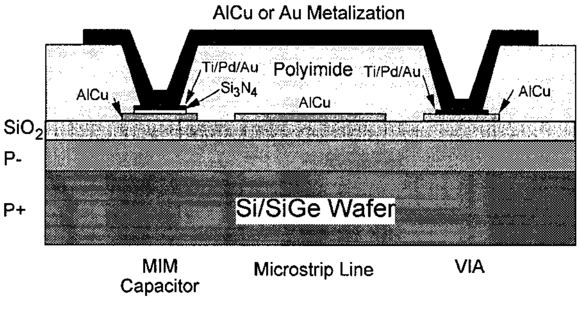

Figure 1. Cross-sectional diagram of our implementation of a Si-based MMIC using polyimide microstrip transmission lines. The polyimide and gold that form transmission lines is deposited on top of conventionally processed Si wafers.

Typical foundry prices range from $1.00/mm^2 for GaAs at low microwave frequencies (<10 GHz) to $10.00/mm^2 for InP mm-wave (>40 GHz) circuits. These costs prohibit commercial use of all but the most simple MMIC or discrete device. The cost of typical high-performance Si and SiGe bipolar technologies range from $0.10 to $0.40/mm^2.

Recent improvements in $Si_{1-x}Ge_x/Si$ heterojunction bipolar (HBT) transistors have increased cutoff frequencies to 50-200 GHz [2,3,4], approaching those of III-V HBTs and even high-electron-mobility transistors (HEMTs). A significant problem with Si based MMICs is the lack of a SI Si substrate. High resistivity silicon has been used [3], however these substrates are often more costly than their III-V counterparts and are not always compatible with standard, industrial Si production lines. The work presented here describes two approaches for integrating distributed elements with high-frequency Si devices: the polyimide microstrip MMIC (figure 1) and the flip-chip MIC (figure 2).

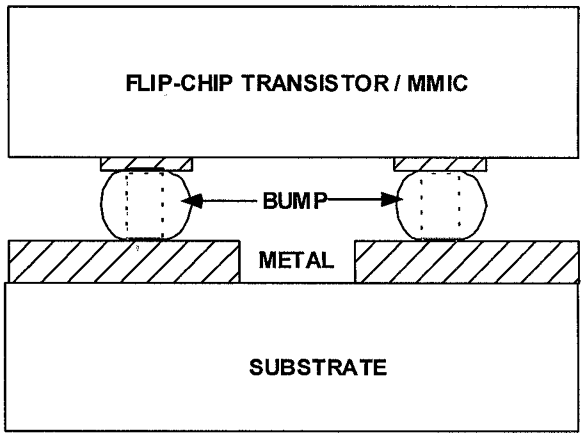

Figure 2. Cross-sectional diagram of a flip-chip MIC. The flip-chip can either be a discrete transistor, or a complex integrated circuit. The active die is attached to the passive substrate using solder bumps.

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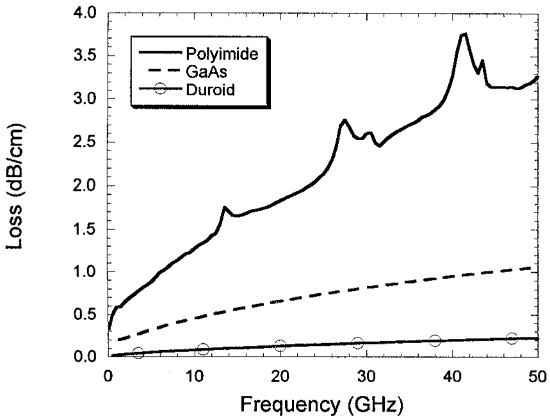

Figure 3. Loss vs. frequency for 50 Ω microstrip transmission lines on three substrates: 250 μm Duroid, 100 μm GaAs, 13 μm polyimide. The polyimide loss is measured data, the others are calculations. Peaks in the measured data result from the measured line being an integer-multiple of a half-wavelength.

Figure 3 shows a comparison between the losses of 50 Ω microstrip transmission lines using three different dielectrics with their typical thicknesses: 250 μm Duroid [6], 100 μm GaAs, 13 μm polyimide [7]. For good dielectrics, the loss of a microstrip line is dominated by metal resistivity, and since a wider metal line is needed for thicker substrates to maintain the desired impedance, a thicker substrate will generally provide lower loss [5].

Polyimide Microstrip MMICs

Polyimide microstrip transmission lines consist of a metal ground-plane that is the top-most layer of metal on a standard processed Si IC wafer, and a thick layer of polyimide which supports the microstrip line (figure 1) [5]. This structure is then a conventional MMIC using the components from a standard Si IC process (transistors, resistors, capacitors, diodes, etc.) under the ground plane with the transmission line elements above. Such a structure makes highly integrated circuits possible, for example, by including microwave circuits (low-noise amplifiers, mixers, oscillators, etc.) on the same chip as signal processing and digital circuitry.

We are currently working with IBM using their 200 mm SiGe bipolar technology [2]. In this variation of a standard Si IC process, we have three levels of metalization normally used for interconnections. We use the top-most layer of metal as a ground-plane for the microstrip transmission lines, but the ground-plane must have openings to allow connections between the lines above the and the devices below.

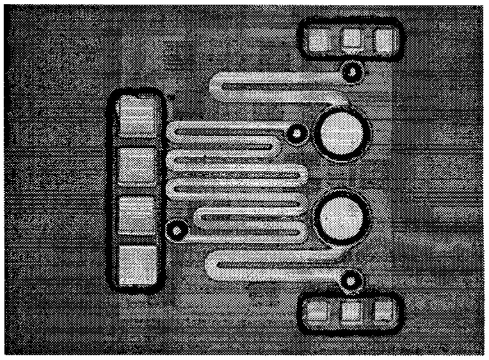

Figure 4. A Ku-Band driver amplifier using polyimide microstrip transmission lines. Large circles are capacitors and small circles are vias between devices under the ground-plane and the microstrip lines.

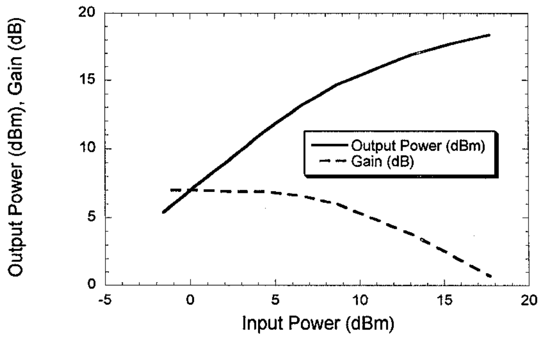

Figure 5. Output power and gain vs. input power for amplifier shown in figure 4. Small-signal gain is 7 dB, and 1 dB compression occurs at 40 mW output power (12 GHz).

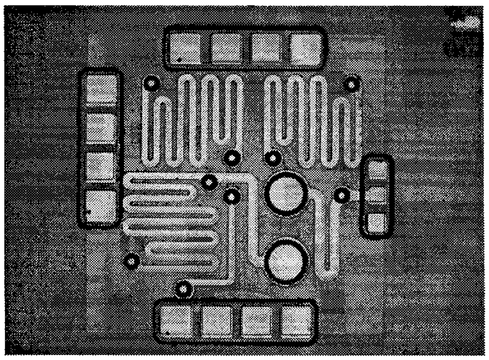

Figure 6. Photograph of a Ku-Band VCO with buffer amplifier. Distributed elements are implemented using polyimide microstrip transmission lines.

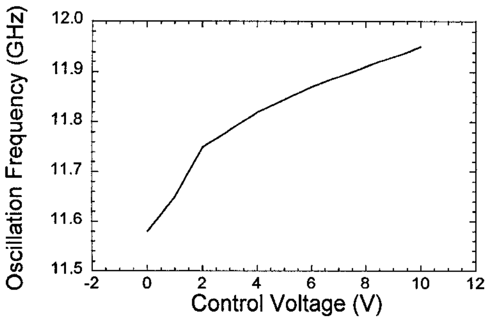

Figure 7. Frequency vs. control voltage for the VCO shown in figure 6.

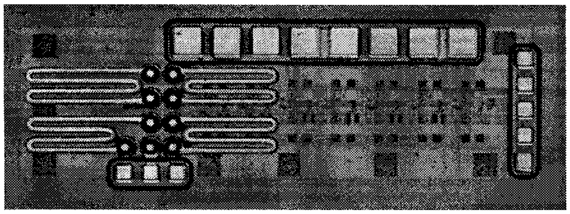

Figure 8. A K-band static frequency divider (÷ 128) implemented with an inductively peaked input buffer (left side of photo).

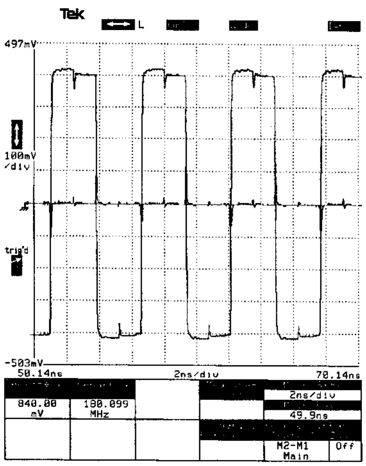

Figure 9. Response of the frequency divider (÷ 128) shown in figure 8. The maximum operating frequency is 23 GHz.

The substrate, devices, interconnects, and the ground-plane are all part of the standard IC process.

We have designed and tested a variety of polyimide MMICs that combine the IBM SiGe HBT devices [2,3] with polyimide dielectric microstrip lines [5]. Figures 4 through 9 show photographs and measured responses of three SiGe MMICs: a Ku-Band amplifier, a Ku-Band VCO, and a K-band frequency divider [8]. An X-band singly-balanced mixer was also reported at [9].

Flip-Chip MICs

Flip-chip IC attachment has been widely used in the IC industry recently to reduce the parasitics associated with the more typical wire bonding to packages. Flip-chip attachment requires one to place a solder bump on the IC's pads. These solder bumps are then placed in contact with their desired pads on the package and heated to melt the solder, forming the connection (figure 2).

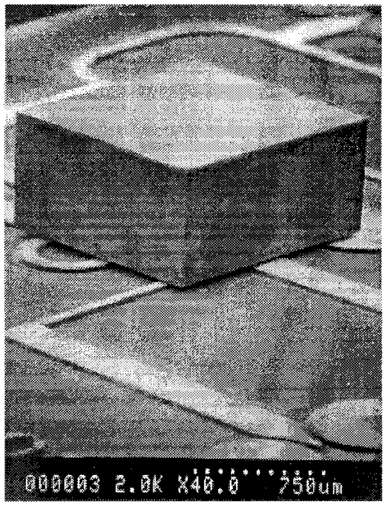

Figure 10. SEM photograph of a Si die flip-chip mounted to a Duroid circuit board. The circuit board contains transmission lines and other distributed elements. This chip is 1300 X 1300 X 750 μm^3.

We use the same flip-chip technique to attach small die (typically discrete transistors) to microwave circuit boards. Figure 10 shows a photograph of a small die flip-chip mounted on a Duroid circuit board. Wire bonding has a large parasitic inductance that can change from bond to bond even in automated systems. The flip-chip MIC combines the repeatable, low parasitic attachment of solder bumps with the small die size and high performance one achieves with the MIC.

The flip-chip MIC approach also allows one to incorporate a variety of technologies in a single circuit. For example, one could use an InP-based HEMT for an LNA , and on the same circuit have a high-speed SiGe A-D converter.

Many more combinations are possible that can take advantage of the combination of technologies.

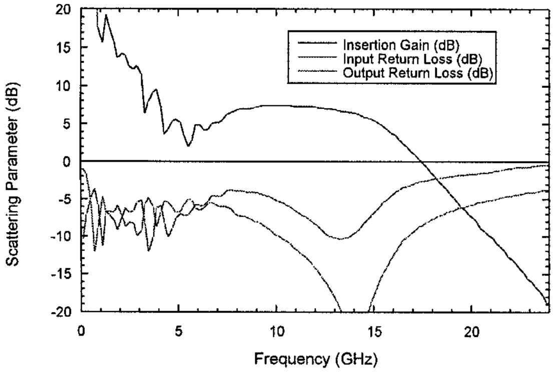

Figure 11. Small-signal response of Ku-Band flip-chip MIC amplifier. The gain is 7 dB over the band of interest.

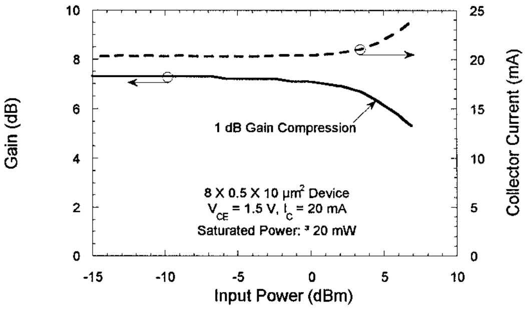

Figure 12. Large-signal response of Ku-Band flip-chip MIC amplifier. 1 dB gain compression occurs at 20 mW output power, ≈ ½ of that from the amplifier in figure 4 (which uses a device 2.5 X larger).

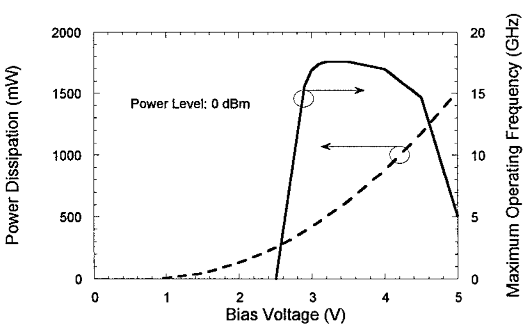

Figure 13. Response of the Ku-Band frequency divider flipped onto a Duroid substrate. This circuit is different from that shown in figure 8 only in that it does not have inductive peaking at the input buffer and uses two additional divider stages (÷ 512).

We have designed and tested several SiGe flip-chip MIC circuits combining the IBM SiGe HBT with passive elements fabricated on 10 mil RO3010 Duroid. Small- and large-signal performance of a Ku-Band amplifier are shown in figures 11 and 12. This amplifier is similar to that shown in figure 4, but with a much smaller device (40 μm^2 compared to 100 μm^2). Characteristics of a Ku-Band frequency divider, similar to that shown figure 8, are shown in figure 13.

Summary

We have demonstrated two approaches (polyimide MMIC and flip-chip MIC) for implementing low-loss distributed elements for integration with Si-based devices. There is a tradeoff that differentiates the two approaches. Although the loss of a transmission line on a thick Duroid board is much lower than that on thin polyimide, the parasitics associated with the lines on the Si-based die feeding the bumps and the bumps themselves impose difficult-to-model and often significant parasitics; while the parasitics associated with the vias in the polyimide MMIC are much smaller.

By combining the performance achievable with the MMIC or MIC approach and the low-cost of Si fabrication (as compared to III-V), the possibility of highly functional consumer microwave products may become reality. There are many applications that require high-volume, low-cost microwave components.

References

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