THREE-DIMENSIONAL MASTERSLICE MMIC ON Si SUBSTRATE

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ABSTRACT

This paper describes Si based three-dimensional MMIC technology. This technology greatly improves the operating frequency of Si MMICs up to the Ku-band and makes them competitive with GaAs MMICs in the higher frequency band. An X-band amplifier and highly integrated single-chip receiver using Si bipolar transistors are demonstrated to highlight the advantages of the Si 3-D MMIC technology. Cost estimation compared with conventional GaAs 2-D MMICs is also discussed.

INTRODUCTION

The forthcoming multimedia era will require highly integrated multifunctional MMICs for mobile communications, satellite communications, wireless LANs, and so on. These applications will require us to make the MMICs cost effective. Si MMICs have great advantages over GaAs MMICs, such as a well-established fabrication process, lower process cost, and the potential for easy integration with digital LSIs.

This paper describes a three-dimensional (3-D) MMIC technology [1] employing a Si substrate. The Si 3-D MMIC technology greatly improves the operating frequency of Si MMICs and makes them competitive with GaAs MMICs in the higher frequency band. As a result, this technology effectively reduces the cost of MMICs and wireless equipment.

OPERATING FREQUENCY

A comparison of the frequency-gain behavior for the R-C coupled amplifier and that of the reactive matching amplifier is shown in Fig. 1. Values of the gain-bandwidth product (*GB*) of the simple R-C coupled amplifier and negative feedback amplifier are constant, and the bandwidth of these amplifiers cannot be extended above the line *GB* = const. which is limited by $f_T/\sqrt{2}$. As a result, the operating frequency of the amplifier is around f_T/5 to f_T/3. On the other hand, reactive matching circuits are usually used to achieve the maximum available gain (MAG) at the upper band edge in the microwave and millimeter-wave band. Then, the operating frequency of the reactive

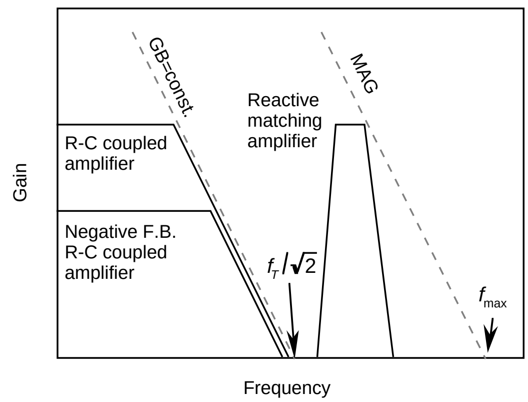

Fig. 1 Frequency-gain behavior for R-C coupled amplifier and reactive matching amplifier.

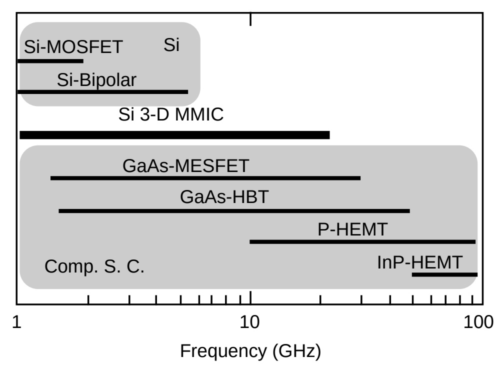

Fig. 2 Applicable frequency band of each device.

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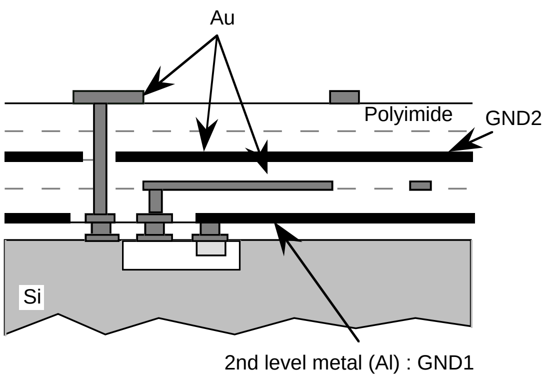


Fig. 3 Basic structure of Si 3-D MMIC.

matching amplifier achieves a level from $f_{max}/3$ to $f_{max}/2$. In the conventional Si MMIC design, the reactive matching technique cannot be effectively used because of the lack of high Q inductors and transmission lines due to non-negligible substrate conductivity. This is the reason why Si MMICs are not available in the higher frequency band.

The 3-D MMIC technology effectively isolates the wafer properties, such as conduction, from passive circuits and makes Si MMICs operate at higher frequencies using high Q components. The technology greatly improves the operating frequency to twice or three-times higher than that of conventional Si MMICs and makes them competitive with GaAs MMICs in the frequency band as shown in Fig. 2.

STRUCTURE OF THE 3-D MMIC

Figure 3 shows the basic structure of the Si 3-D MMIC. Transistors, resistors, and lower electrodes of MIM capacitors are formed on a Si substrate and passivated. The second level metal (Al) is formed on the passivation film and covers most of the wafer surface. The devices and the metals are formed using an ordinary Si IC process. After that, a three-dimensional passive structure constructed with polyimide films and gold metals (Au) is formed on the second level metal. The fabrication process of the 3-D structure is almost the same as that of GaAs 3-D MMICs [2]. By using the second level metal as a ground plane (GND1), the conductive property of the wafer is effectively isolated from passive structures created on GND1, and high Q passive circuits are available. This allows the use of a reactive matching technique for Si MMIC design and greatly improves the operating frequency of the Si MMICs. This structure also offers highly integrated multifunctional MMICs and Masterslice MMICs which are the same as those we

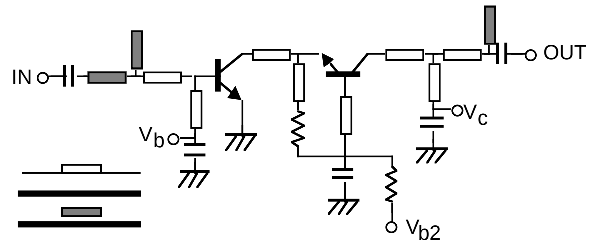
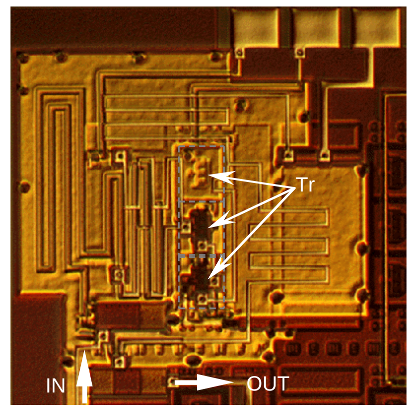


Fig. 4 Circuit scheme of the fabricated X-band amplifier using cascode Si bipolar transistors.



SIZE: 0.73 × 0.77 mm

Fig. 5 Microphotograph of the fabricated X-band amplifier.

demonstrated using a GaAs substrate in [3] and [4]. The high integration technology effectively enhances the integration to a level three to five times those of conventional 2-D MMICs. The 3-D Masterslice MMIC technology reduces development turn-around-time (TAT) and fabrication cost. It also eliminates the high level design skill necessary for MMIC design.

CIRCUIT DESIGN

The ground plane of the second level metal (GND1), which separates the wafer and the 3-D passive circuits, enables Si MMICs to be designed in the same way as GaAs MMICs. We first examined the X-band amplifier shown in Fig. 4. The amplifier is constructed with cascode Si bipolar transistors (SST1C [5]), TFMS lines, and triplate TFMS lines for reactive matching. Figure 5 shows a microphotograph of the amplifier fabricated using 3-D masterslice MMIC technology. The single-stage amplifier occupies only a 0.73 × 0.77 mm area. Figure 6 shows the measured performance of the fabricated amplifier. A gain of 8 dB is obtained over 7 to 10 GHz at a collector voltage V_c = 4 V (2 V for each transistor) and the

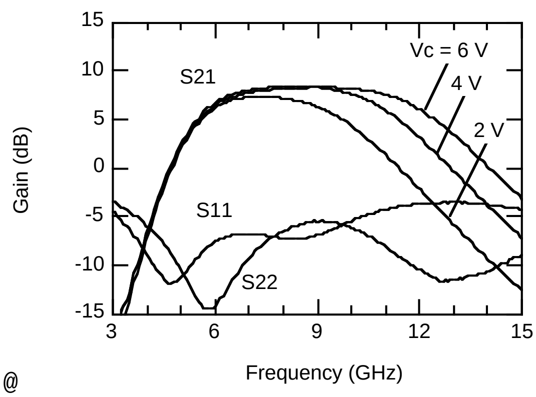
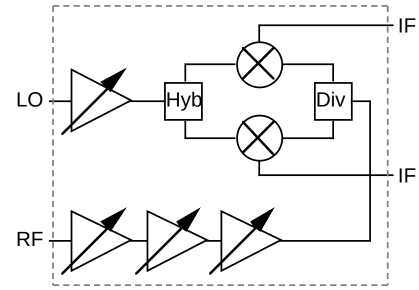


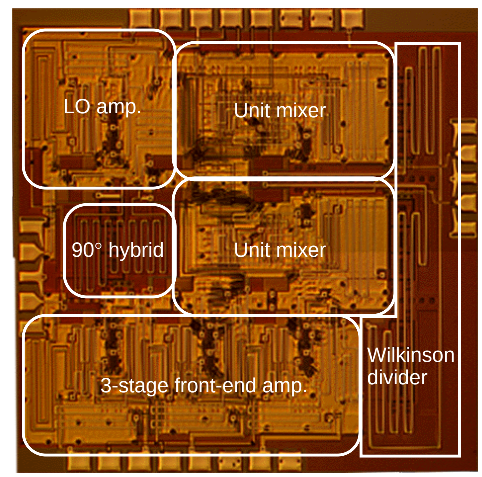
Fig. 6 Measured performance of the fabricated amplifier.

operating frequency achieves 12 GHz at V_c = 6 V. Each transistor has nine 0.3 × 13.4-µm-emitters and the measured f_{max} is around 30 GHz at V_{ce} = 1 V because the transistor is a multi-emitter transistor for analog application (40 GHz for digital). The operating frequency nearly achieves f_{max} /3. The other components, such as VCOs and mixers also exhibited excellent performance in the frequency band.

Figure 7 shows a block diagram and a microphotograph of the fabricated X-band highly integrated single-chip receiver which includes a three-stage front-end amplifier, an LO amplifier, and an image-rejection mixer in a 2.3 × 2.3 mm chip. Figure 8 shows the measured performance of the fabricated single-chip receiver. A 15- to 20-dB gain and better than 20 dB image-rejection ratio are obtained in the X-band.



(a) Block diagram



2.3 × 2.3 mm @ X-band

(b) Microphotograph

Fig. 7 Fabricated X-band single-chip receiver which includes a three-stage front-end amplifier, an LO amplifier, and an image-rejection mixer in a 2.3 × 2.3 mm chip.

COST REDUCTION

Cost estimation of the Si 3-D MMIC is shown in Fig. 9 compared with conventional 2-D GaAs MMICs. The 3-D and Masterslice MMIC technologies reduce cost by more than 50% due to its high integration level even if an additional 3-D process is necessary. The Masterslice technology further reduces the fabrication cost because the masterslice substrate can be mass produced and the TAT is much shorter while still maintaining a high integration level. Finally, Si 3-D MMICs effectively have a lower cost due to their lower process costs and larger wafers. The result is a cost reduction of about 95% from conventional GaAs 2-D MMICs.

CONCLUSION

The 3-D MMIC technology greatly improves the operating frequency of Si MMICs up to the Ku-band and makes them competitive with GaAs MMICs in the frequency band. The Si 3-D MMICs using BJTs, CMOSs and BiCMOSs also have the potential to be easily integrated with digital LSIs as well as low cost. This technology promises to achieve cost effective intelligent wireless communication systems and take us into the forthcoming multimedia era.

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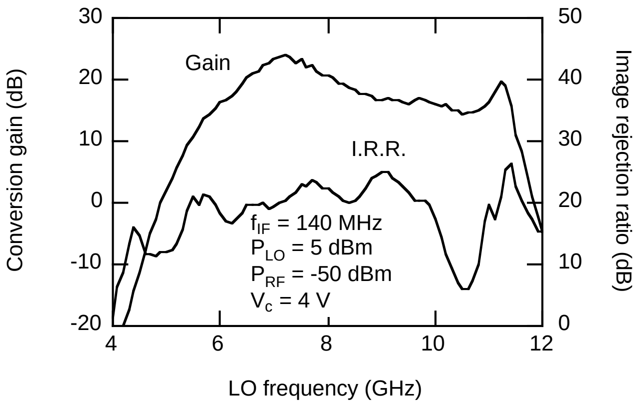

Fig. 8 Measured performance of the fabricated single-chip receiver.

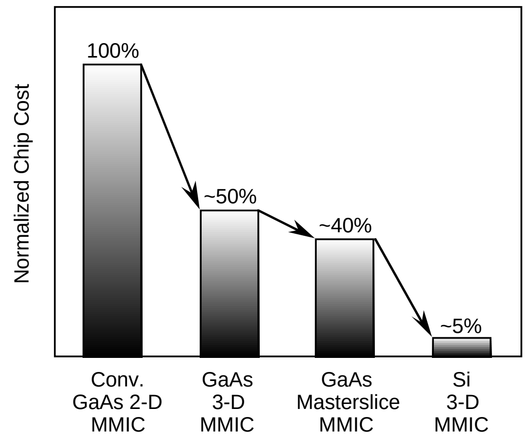

Fig. 9 Estimated cost reduction effect of Si 3-D MMIC.

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