180 Degree Hybrid (Rat-Race) Junction on CMOS Grade Silicon with a Polyimide Interface Layer

George E. Ponchak and John Papapolymerou[1]

Abstract--180-degree hybrid junctions can be used to equally divide power between two output ports with either a 0 or 180-degree phase difference. Alternatively, they can be used to combine signals from two sources and output a sum and difference signal. The main limitation of implementing these on CMOS grade silicon is the high loss associated with the substrate. In this paper, we present a low loss 180-degree hybrid junction on CMOS grade (15 Ω-cm) silicon with a polyimide interface layer for the first time. The divider utilizes Finite Ground Coplanar (FGC) line technology, and operates at a center frequency of 15 GHz.

Index Terms--Silicon, RFIC, hybrid coupler

I. INTRODUCTION

Low cost RF and microwave monolithic integrated circuits (RFIC and MMIC) integrated with digital circuits on the same chip has created a strong interest in silicon as a microwave substrate, especially with the development of SiGe Heterojunction Bipolar Transistors with a high frequency of oscillation [1-3]. However, traditional distributed microwave circuits reliant on transmission lines such as filters, matching circuits, and couplers have high loss due to the low resistivity of the silicon substrate commonly used for BiCMOS and CMOS integrated circuits.

To overcome this problem, two different approaches have been implemented. In the first approach, high resistivity Si wafers are used (ρ>2500 Ω-cm), which has the advantage that traditional microwave components have a similar performance to those on insulating substrates such as GaAs [4]. In the second approach, dielectric layers such as polyimide are used on top of the CMOS substrate to create an interface layer that can host low loss microwave components. Both microstrip and coplanar waveguide transmission lines fabricated this way have exhibited low attenuation for an optimum polyimide thickness [4-5]. Recently, Finite Ground Plane (FGC) coplanar waveguide folded-slot antenna [6], filters [7], and Wilkinson power dividers [8] have been demonstrated on such a substrate configuration with very promising results.

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180-degree hybrid (rat race) junctions as shown in Figure 1 are a critical circuit component for balanced mixers, antenna manifold networks, and power amplifiers. If power is fed into port 1, it is split equally and in phase between ports 2 and 3, and port 4 is isolated. If power is fed into port 2, it is split equally and with a 180-degree phase difference between ports 1 and 4, and port 3 is isolated. Alternatively, the junction can be operated as a combiner by applying power into ports 2 and 3, which results in the sum and difference of the two signals at ports 1 and 4 respectively.

In this paper, we report for the first time a distributed 180-degree hybrid junction fabricated on 15 Ω-cm silicon with a polyimide interface layer. Measured hybrid junction characteristics are presented and compared to the ideal circuit characteristics.

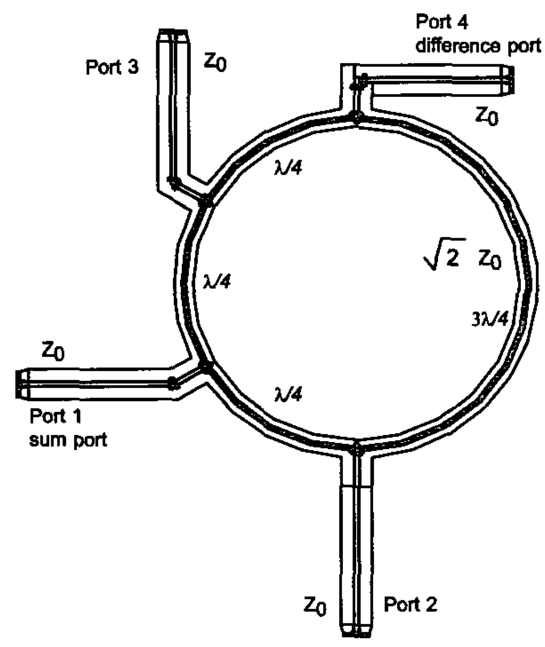

Figure 1: Schematic of 180-degree hybrid junction implemented in finite ground coplanar waveguide.

II. CIRCUIT DESIGN

The Z_0=50 Ω rat race junction is designed for 15 GHz and implemented in FGC on a 15 Ω-cm Si wafer. To decrease the insertion loss associated with placing RF transmission lines directly on the Si wafer, a polyimide interface layer is

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used to reduce the electromagnetic field interaction with the Si. Here, a 20 μm thick layer of Dupont PI-2611 polyimide is spun onto the wafer in four, 5 μm thick layers. Each layer of polyimide is fully cured at 340 C for 120 minutes before the next layer was added. PI-2611 polyimide has a relative dielectric constant of 3.12 measured at 1 MHz [9] and a loss tangent of 0.002 measured at 1 kHz [10]. The hybrid junction is fabricated on the top surface and the bridges required to tie the ground planes together at the "T" junctions, as shown in Figure 1, are fabricated on the third layer, which is 15 μm from the Si. Via holes through the fourth, 5 μm layer connect the two layers. The FGC geometry is chosen to yield the lowest loss on this Si wafer and polyimide combination [5]; Referring to Figure 2, S, W, and B are 74, 8, and 222 μm respectively for the 50 Ω lines and 42, 16, and 126 μm for the 70.7 Ω lines.

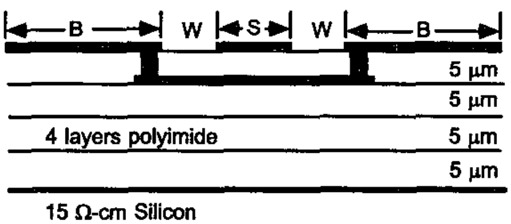

Figure 2: Schematic of FGC on polyimide interface layer on Si.

A Method of Moments (MoM) analysis implemented through Sonnet software is used to determine the characteristic impedance and propagation constant of the FGC lines. Figure 3 shows the MoM predicted effective permittivity (ε_{eff}) for the 70.7 Ω FGC line on the polyimide interface layer. Using the MoM predicted ε_{eff}, the hybrid junction was designed around the center frequency of 15 GHz using ideal transmission line analysis with no correction for FGC line dispersion or parasitic reactance caused by the "T" junctions. The resulting hybrid junction has a radius of 2978 μm.

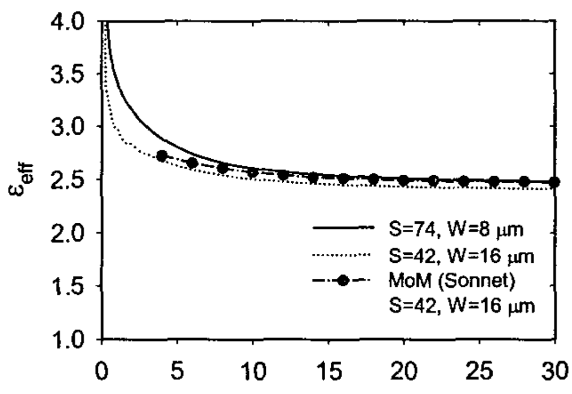

Figure 3: Measured and MoM determined effective permittivity of FGC lines.

The theoretical characteristics of the hybrid junction, including a 500 μm length of line at each port, are determined using ideal transmission line analysis that assumes lossless, dispersionless transmission lines. These characteristics are shown in Figures 4-6. The in-phase power divider amplitude balance is 0.05 dB and the bandwidth for 10 degree phase balance is 50 percent. The 180-degree power divider amplitude balance is 0.05 dB. The return loss at all four ports is 15 dB or greater at 15 GHz.

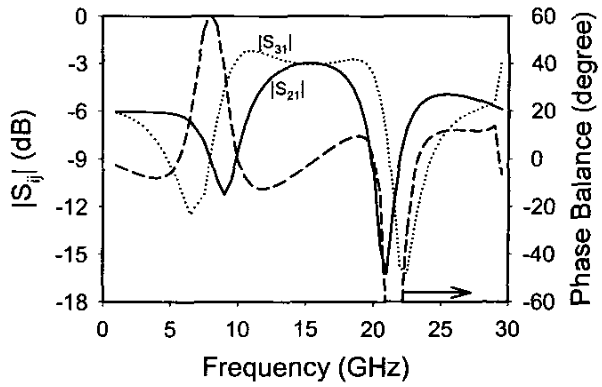

Figure 4: Theoretical characteristics of the in-phase power divider.

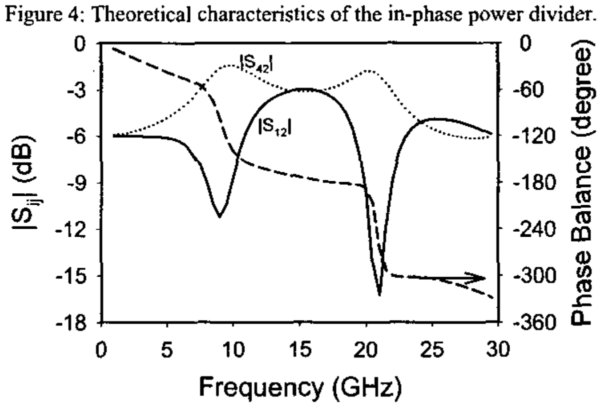

Figure 5: Theoretical characteristics of the 180-degree phase difference power divider.

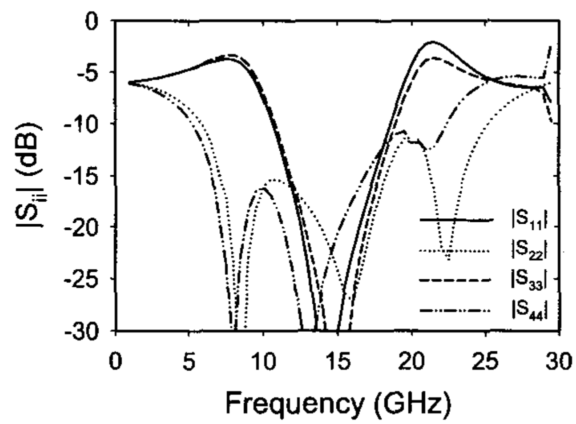

Figure 6: Theoretical return loss characteristics of the hybrid junction.

III. Measurement Technique

The FGC propagation characteristics are measured with a vector network analyzer and probe station. A quartz spacer between the Si substrate and the probe station wafer chuck is used to eliminate parasitic microstrip and parallel plate waveguide modes during testing. The propagation constant, $\gamma=\alpha+j\omega\sqrt{\varepsilon_{eff}}/c$ where α is the attenuation constant, ω is the angular frequency, and c is the velocity of light in vacuum, is deembedded through the Thru-Reflect-Line (TRL) calibration routine implemented in the software program MULTICAL [11]. For each FGC line characterized, four delay lines with the longest line being 1 cm are used in addition to the thru line to enhance accuracy from 1 to 30 GHz. The reference planes are set by the calibration to be 500 μm from the "T" junctions of the hybrid junction. The actual circuit for experimental characterization is shown in Figure 1. During characterization, two of the four ports are terminated with RF probes with integrated 50 Ω terminations.

IV. RESULTS

The measured propagation characteristics for the 50 and 70.7 Ω lines are shown in Figures 3 and 7. The ε_{eff} of the two lines are shown in Figure 3, where it is seen that the measured and MoM predicted values agree very well. The measured attenuation is shown in Figure 7. At 15 GHz, the attenuation of the 50 and 70.7 Ω FGC lines is 2.67 and 1.89 dB/cm respectively. Since the reference planes are 500 μm from the junction, all of the through measurements, for example S_{21}, S_{31}, S_{24}, include 0.267 dB of extra insertion loss. Based on the measured attenuation of the 70.7 Ω lines, the λ/4 line sections of the hybrid junction each contribute 0.59 dB of insertion loss.

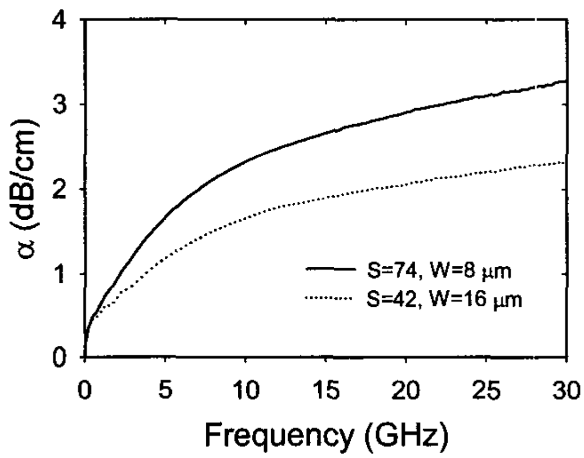

Figure 7: Measured attenuation of the FGC lines used in the hybrid junction.

The measured results for the hybrid junction are shown in Figures 8 through 11. First, by comparing Figures 4 through 6 with Figures 8 through 11, it is seen that the measured characteristics match the theoretical characteristics very well except for the FGC line insertion loss. In Figure 8, the in-phase power divider characteristics are shown. The average measured insertion loss at the two ports is 1.65 dB and the phase balance is within 10 degree over a 66 percent fractional bandwidth. The 180-degree phase difference power divider characteristics are shown in Figure 9, where it is seen that the average insertion loss at the two ports is 2.05 dB and the phase difference is 180 degree at 15 GHz. For all four ports, the return loss is 15 dB or higher, but there is a slight downward shift in frequency to 13 GHz as predicted by in Figure 6. The isolation at port 4 when fed at port 1 and at port 3 when fed at port 2 is the same because of symmetry. The measured isolation is shown in Figure 11 where it is seen that the isolation is greater than 30 dB at 15 GHz and greater than 15 dB over an 8.5 GHz bandwidth.

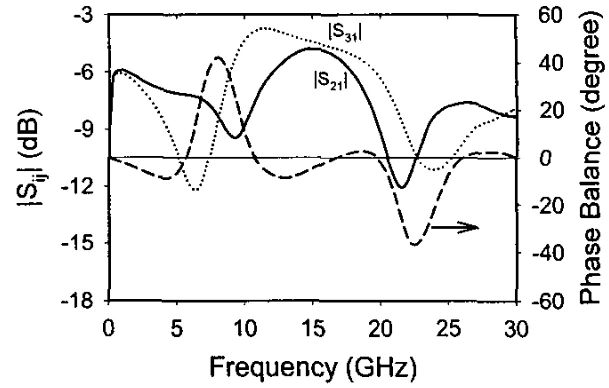

Figure 8: Measured characteristics of the in-phase power divider.

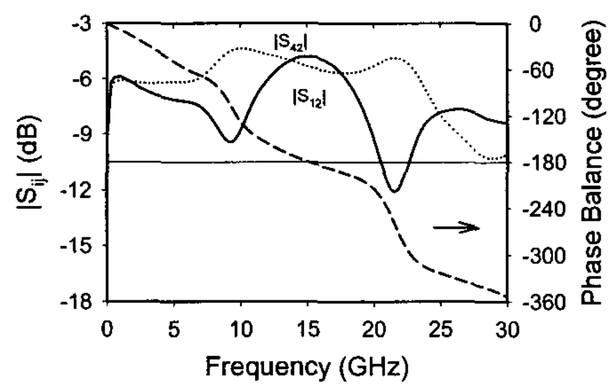

Figure 9: Measured characteristics of the 180-degree phase difference power divider.

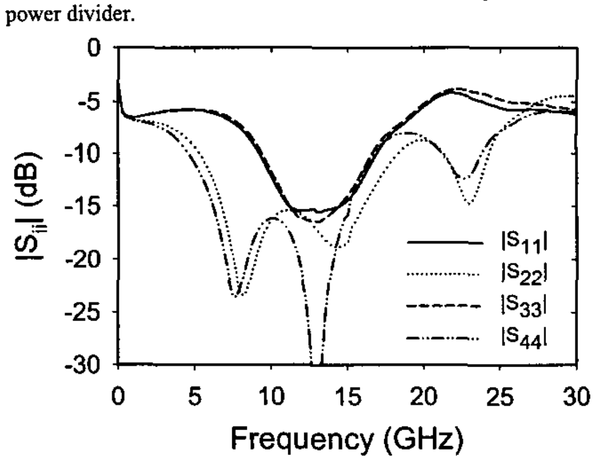

Figure 10: Measured return loss characteristics of the hybrid junction.

V. CONCLUSIONS

A 180-degree hybrid junction has been demonstrated on a 15 Ω-cm silicon wafer with a 20 μm polyimide interface layer. The measured and theoretical characteristics of the circuit agree very well, indicating that the effect of the lossy silicon wafer has been minimized. A summary of the measured and predicted hybrid junction characteristics is shown in Table 1, where the insertion loss of the measured characteristics is corrected for the 500 μm feed lines. The agreement between the two is very good, and the junction insertion loss is almost entirely predicted by the attenuation of the FGC lines. Furthermore, with only 1.58 dB average insertion loss, the 180-degree hybrid junction developed here is suitable for wireless and microwave circuits on 15 Ω-cm Si wafers.

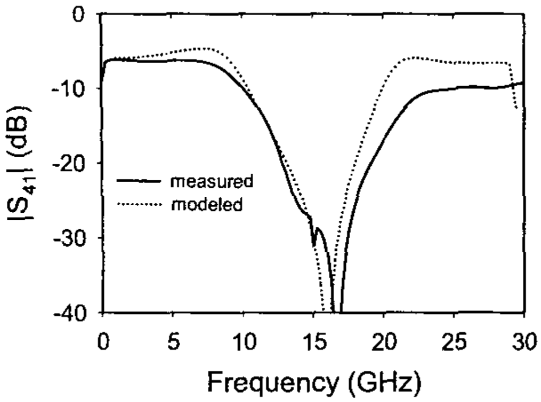

Figure 11: Measured and modeled isolation of the hybrid junction.

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	Theoretical in-phase divider	Measured in-phase divider	Theoretical 180-degree divider	Measured 180-degree divider
Average insertion loss	0 dB	1.38 dB	0dB	1.78 dB
Amplitude balance	± 0.05 dB	± 0.15 dB	± 0.05 dB	± 0.25 dB
10° phase balance fractional bandwidth	50 %	66 %	40 %	21.6 %
15 dB isolation fractional bandwidth	45 %	56 %	45 %	56 %

Table 1: Summary of measured 180-degree hybrid junction characteristics (corrected for feed line losses) compared to ideal transmission line circuit characteristics of the same junction.