Millimeter-Wave Silicon MMIC Interconnect and Coupler Using Multilayer Polyimide Technology

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***Abstract*—This paper reports our latest progress in developing low-loss and low-crosstalk silicon MMIC interconnects for millimeter-wave applications. The proposed silicon/metal/polyimide (SIMPOL) structure based on multilayer polyimide technology is extremely effective in reducing noise crosstalk, and also provides very low line loss, even at the millimeter-wave regime. The measurement results of the developed SIMPOL structures demonstrate extremely low noise crosstalk (<-40 dB) in the entire frequency range (up to 50 GHz), which is limited by the dynamic range of the measurement equipment, and excellent insertion loss (<-0.25 dB/mm) up to 45 GHz. In addition, the SIMPOL concept is applied for the first time successfully in the design and fabrication of branch-line hybrids at millimeter-wave frequencies, 30 and 37 GHz.**

***Index Terms*—Branch-line hybrid, crosstalk, insertion loss, interconnect, mixed-signal MMIC, noise isolation, silicon IC.**

I. Introduction

With the strong demand on advanced wireless communication services for broadband digital data communications, highly integrated circuits such as mixed-signal IC's and advanced system-on-a-chips have attracted a great deal of attention, due to their significant benefits such as overall chip size reduction, lower fabrication cost, as well as enhanced system performance. This is particularly true for very-high-frequency wireless communication systems because it provides an additional benefit of mitigating the severe transmission line loss at very high frequencies. Meanwhile, significant progress in silicon devices, such as high-speed SiGe HBT's ($f_{\max}>$ 160 GHz) [1], has made it possible to realize silicon-based mixed-signal MMIC's and system-on-a-chip at millimeter-wave frequencies. However, serious noise-crosstalk between digital and RF/analog circuits and significant transmission line loss on conductive silicon substrates have mainly limited the applications of the high-frequency devices to high-frequency MMIC's.

Numerous efforts have been made to reduce signal loss and noise crosstalk in these high-frequency MMIC's. Micropackaging, providing reasonably good performance in noise crosstalk and insertion loss, might be an attractive solution, but the cost effectiveness of the technique has yet to be fully addressed [2], [3].

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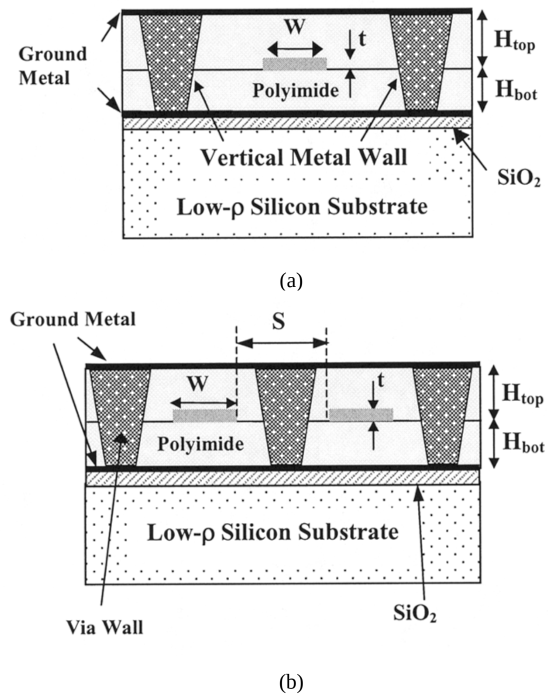


Fig. 1. Cross-sectional views of the fabricated SIMPOL interconnect. (a) Single-channel interconnect. (b) Two-channel interconnect. (Parameters are shown in Table I.)

In this paper, we present our recent progress in implementing the silicon/metal/polyimide (SIMPOL) structure, a novel interconnect concept for broadband ($>$ 50 GHz) mixed-signal silicon MMIC's using multilayer polyimide technology. It provides several significant advantages over conventional microstrip-type structures, such as extremely low noise crosstalk, low signal loss, and cost effectiveness [4], [5]. Prototype test structures including branch-line hybrids at millimeter-wave frequencies have been designed and fabricated. The measurement results demonstrate the superior performance of the SIMPOL in noise isolation and insertion loss, and also denote its applicability to advanced millimeter-wave wireless communication systems.

II. Design and Fabrication of SIMPOL Interconnect

Compared to conventional microstrip-based interconnect structures, the proposed SIMPOL structure provides several

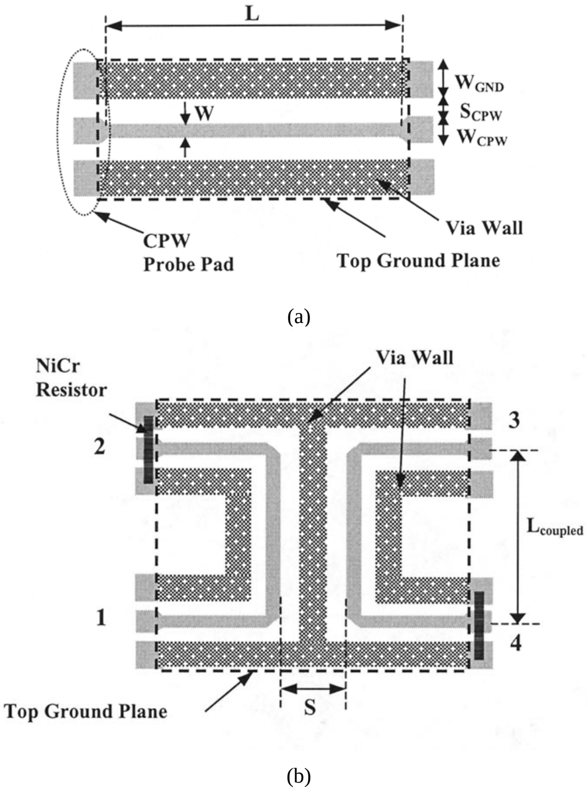


Fig. 2. Layout of the fabricated SIMPOL interconnect. (a) Uniform transmission line. (b) Coupled lines ($L = 4$ mm, $W_{\rm GND} = 150$ μm, $S_{\rm CPW} = 64$ μm, $W_{\rm CPW} = 90$ μm, $L_{\rm coupled} = 1000$ μm, $S = 150$ μm).

advantageous features such as extremely low crosstalk even at very high frequency range ($>$ 50 GHz), low insertion loss by using low-loss polyimide layers, broadband performance, and cost effectiveness by using CMOS-grade low-cost low-resistive silicon substrate. The detailed configuration and characteristics are described in [4].

As an evaluation step of the proposed SIMPOL, a simplified SIMPOL test structure which does not have the recessed area in the silicon substrate is fabricated as shown in Fig. 1. However, the modified model should offer corresponding performances to the original SIMPOL structure with respect to the performance parameters such as noise crosstalk and insertion loss. The fabrication procedures of the simplified SIMPOL interconnect is described in [4].

In order to address the fundamental performance of the proposed SIMPOL structure as an interconnect, two types of components have been designed and fabricated. Fig. 2(a) and (b) shows the layouts of the fabricated uniform lines and coupled lines used to characterize the insertion loss and noise crosstalk parameters of the SIMPOL structure. In the new design, every single line is completely shielded by vertical metal walls as shown in Fig. 2. This complete isolation has improved the accuracy in the crosstalk measurements by preventing indirect coupling through the substrate between the lines. Fig. 3 shows the photographs of fabricated components. The profile of the fabricated SIMPOL is denoted in Table I.

The coplanar waveguide (CPW) probing pads and CPW-to-stripline transitions are not a part of the SIMPOL interconnect. However, since they have a significant effect on the accuracy

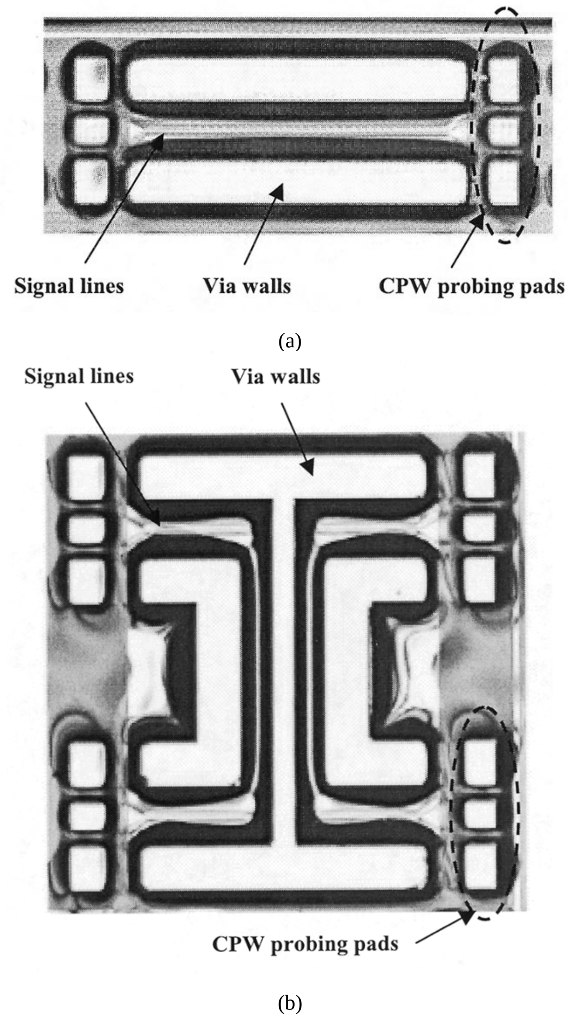


Fig. 3. Photographs of the fabricated SIMPOL interconnect. (a) Uniform transmission line. (b) Coupled lines.

of the high-frequency S-parameter measurements, they should be treated as carefully as the SIMPOL interconnect for reliable measurement results. Impedance mismatch and abrupt mode conversion in a poorly designed CPW-to-stripline transition will cause inaccuracy and severe ripples in the measurement data which are difficult to calibrate out. We have observed that one of the most critical areas of the CPW-to-stripline transition is the location of the top-ground planes. As shown in Fig. 4, full coverage of the tapered signal lines with the top ground metal provides a smooth transition from CPW mode to stripline mode and improves the measurement accuracy substantially. The length of the tapered line, $L_{\rm taper}$ in Fig. 4, also affects the measurement, but the effect is not as significant as the previous parameter, and determined to be 60 μm.

III. Measurement of SIMPOL Interconnect

The S-parameters of the fabricated test structure were measured on an HP 8510C network analyzer, using a pair of GGB Picoprobes with 150-μm pitches (50 A-GSG-150-LP). A short-open-load-thru (SOLT) calibration was carried out for the frequency range from 1 to 50 GHz with a standard calibration set (CS-5) for stable calibrations.

TABLE I
PROFILE OF THE SIMPOL TEST STRUCTURE

	Maximum Value	Minimum Value
First Polyimide Layer Thickness	13.77 μm	13.04 μm
Total Polyimide Layer Thickness	27.41 μm	26.94 μm
Transmission Line (Ti/Al) Thickness	1.6 μm	1.6 μm
Bottom Metal (Ti/Al) Thickness	1.0 μm	1.0 μm
Top Metal (Ti/Al) Thickness	0.5 μm	0.5 μm
Resistor (NiCr) Value	50.1 Ω	50.1 Ω

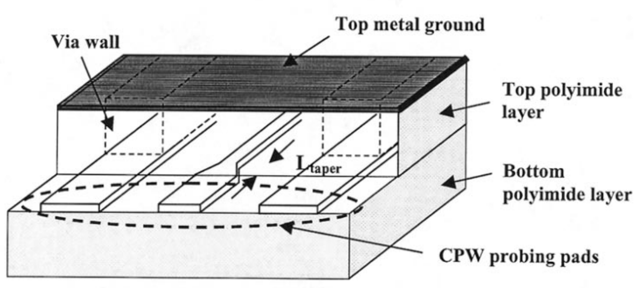
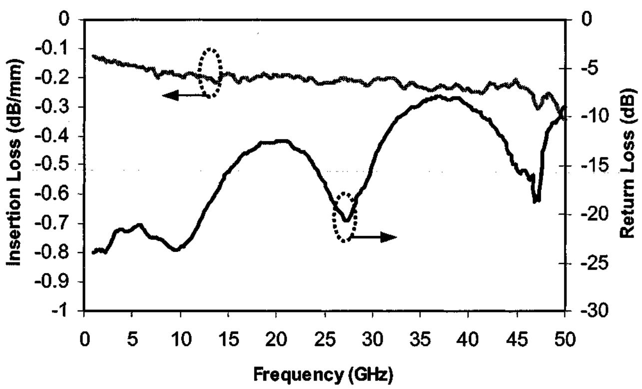
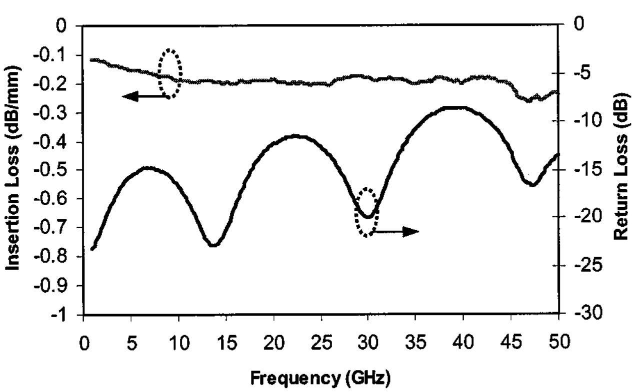


Fig. 4. Detailed configuration of CPW-to-stripline transition and CPW probing pads ($L_{taper} = 60$ μm).



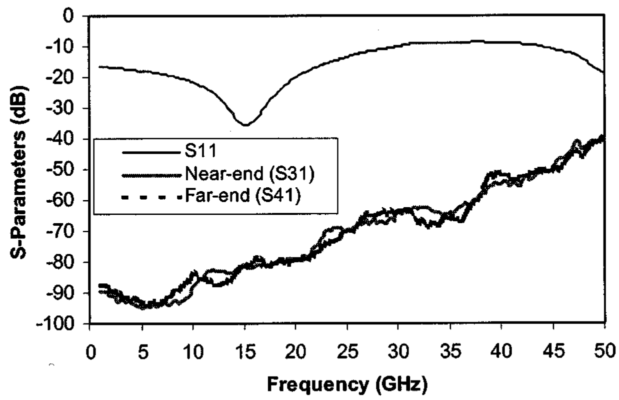
(a)



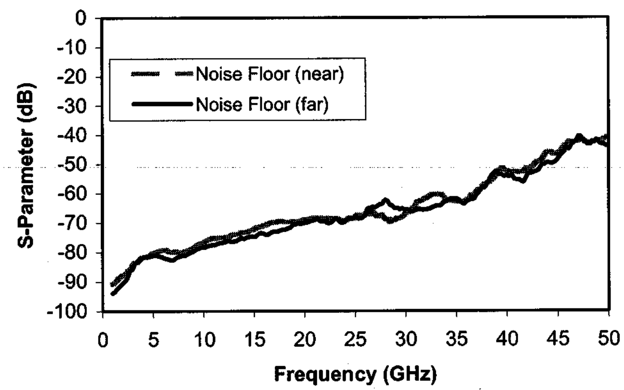
(b)

Fig. 5. Insertion loss and return loss measurement of the SIMPOL uniform lines shown in Fig. 2(a). (a) Line width $(W) = 15$ μm (45 Ω). (b) Line width $(W) = 20$ μm (38 Ω).

After calibration, we first measured the insertion loss of 4-mm-long straight lines as shown in Fig. 2(a). With the new design of the CPW-to-stripline transition, the accuracy of the measurement has been improved considerably compared to the previous measurement [5]. Fig. 5(a) and (b) shows the measured insertion losses per unit length (1 mm) and the return losses for the lines with the widths of 15 and 20 μm, respectively. In order to characterize the pure insertion loss (metal and dielectric loss) of the SIMPOL structure, insertion loss is defined and calculated from the measured S_{21} and return losses by subtracting the amount of the return loss from the amount of the measured S_{21}. The insertion loss of the wider line, as anticipated, is slightly lower than that of the narrower one mainly due to the lower metal loss, but in both cases very good and smooth insertion losses (<-0.25 dB/mm up to 45 GHz) are achieved with reasonably good return losses in the entire frequency range. The sudden degradation of the insertion losses at the higher frequency end ($>$45 GHz) is probably caused by increased calibration tolerance at the higher frequencies.



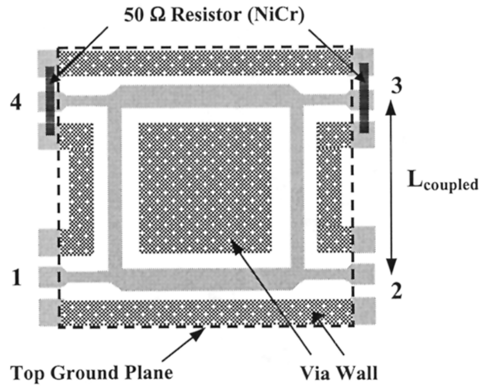
(a)



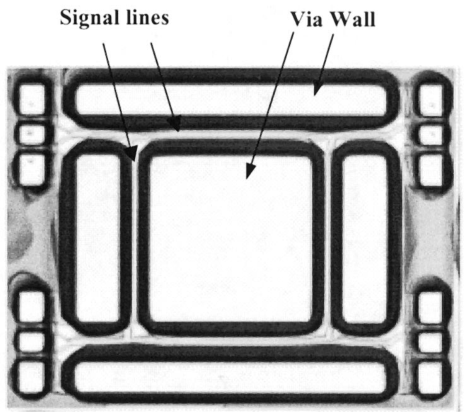
(b)

Fig. 6. Noise crosstalk and return loss measurement of the SIMPOL coupled lines shown in Fig. 2(b). (a) Noise coupling and return loss ($W = 15$ μm). (b) Noise floor level.

Meanwhile, the noise crosstalk of the coupling structures shown in Fig. 2(b) is measured, and the results are shown in Fig. 6(a) along with the return loss. Due to the completely enclosed architecture of the SIMPOL structure, the coupled noise level is expected to be extremely low even at the high frequency end (50 GHz). Both the near-end coupling and the far-end coupling show excellent isolation levels (<-3 dB up to 30 GHz and <-40 dB up to 50 GHz) in the entire frequency



(a)

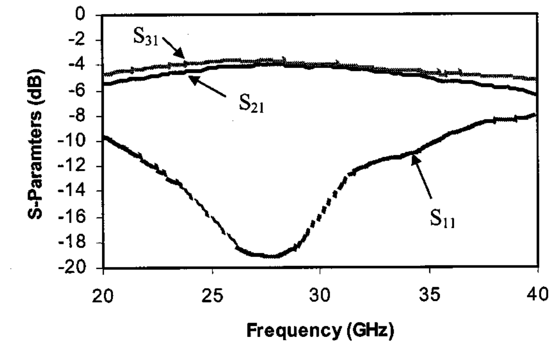


(b)

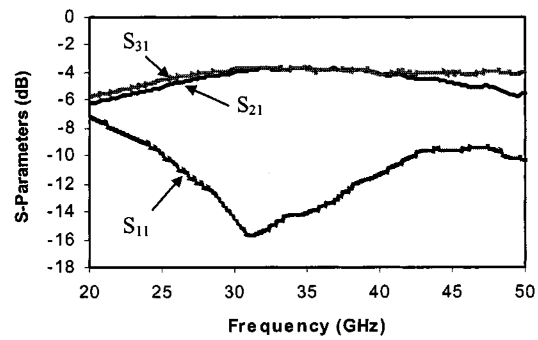
Fig. 7. Fabricated SIMPOL branch-line hybrid. (a) Layout drawing of the designed hybrid. (b) Photograph of the fabricated hybrid.

range. The measured coupling levels are noticeably improved compared with the previous results where the coupling levels above 30 GHz are slightly higher than the noise floor level by 5–10 dB [5], which is caused by indirect coupling through the substrate. This improvement is accomplished by two enhanced design parameters: CPW-to-stripline transition design and complete shielding of individual lines. This result implies significant amount of power propagates to the substrate and couples to neighboring circuits. The improved transition diminishes the discontinuity effect and the substrate propagation, and individual shielding prevents the coupling of the propagated power to the other line.

Furthermore, the monotonic increase of the coupling level is caused mainly by the test system dynamic range limitation, not by the imperfection of the SIMPOL structure. Fig. 6(b) shows the measured background noise level, which corresponds to the transmission coefficient when the two probes are suspended in the air by 5mm while maintaining identical distance to that of the SIMPOL test structure. The noise floor is considered as the maximum sensitivity of test equipments. The measured coupling levels (S_{31} and S_{41}) are exactly at the same level of the noise floor. It represents that the isolation of the SIMPOL is as high as the test equipment measures, and that higher isolation level can be demonstrated as long as test equipments provide higher dynamic range.



(a)



(b)

Fig. 8. S-parameter measurement of the SIMPOL branch-line hybrids. (a) 30-GHz branch-line hybrid ($L_{\mathrm{coupled}} = 1372\ \mu$m). (b) 37-GHz branch-line hybrid ($L_{\mathrm{coupled}} = 1089\ \mu$m).

IV. Branch-Line Hybrid Application

The SIMPOL interconnect is extremely effective at noise isolation, with an excellent level of signal loss even at millimeter-wave frequencies. This is demonstrated in the previous section by measuring simple structures such as uniform lines and coupled lines. In order to extend the SIMPOL concept to millimeter-wave circuit components, branch-line hybrids have been designed and fabricated at 30 and 37 GHz with the potential applications to millimeter-wave wireless communication circuits. Fig. 7(a) and (b) shows the layout and the photograph of a designed coupler.

A branch-line hybrid is a popular 3-dB directional coupler which splits incoming power into two output ports at the same level with a 90° phase difference while no power is coupled to the remaining isolated port. Power splitting ratio of the two outputs is the critical figure of merit of a branch-line hybrid [6].

In order to measure four-port branch-line hybrids with a two-port measurement system, the two idling ports must be terminated with resistive loads (50 Ω). Mismatching of the idling port may cause a severe inaccuracy in the S-parameter measurement, and the performance cannot be predicted in a reliable manner.

Fig. 8(a) and (b) shows the measured S-parameters of the branch-line hybrids at 30 and 37 GHz, respectively. Both hybrids perform excellent power-splitting ratios along with good return losses. The 30-GHz hybrid shows the measured output powers of −4.12 and −3.95 dB at the port 2 and 3 at 30 GHz, and the 37 GHz hybrid shows the output powers of −3.73 dB and −3.76 dB at 37 GHz. The loss of the 30-GHz hybrid is observed greater than that of the 37-GHz hybrid. This is because the physical size of the hybrid at 37 GHz (1089 μm) is smaller than that at 30 GHz (1372 μm) while the loss per unit length at 37 GHz (0.232 dB/mm) is only slightly higher than the loss at 30 GHz (0.205 dB/mm).

When the bandwidth of a hybrid is defined as where two outputs have relative magnitude differences less than 0.2 dB, the measured bandwidths of the designed hybrids demonstrate 3.18 GHz for the 30 GHz hybrid and 10.53 GHz for the 37G Hz hybrid, respectively.

V. Conclusion

We have presented a novel interconnect concept for broadband silicon MMIC implementation. The prototype measurement results demonstrate that the SIMPOL structure is extremely effective in reducing the noise coupling between adjacent transmission lines (<-40 dB up to 50 GHz). The insertion line loss is also very low (<-0.25 dB/mm up to 45 GHz) with easily achievable thick polyimide layer (27 μm). The successful application of the SIMPOL structure to branch-line hybrids at millimeter-wave frequencies (30 and 37 GHz) indicates that this novel SIMPOL structure should provide an attractive solution for low-cost high-performance wireless application up to millimeter-wave frequencies.

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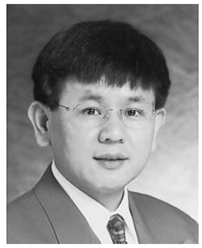

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