Minimizing Attenuation of Coplanar Waveguide on Lossy Silicon Substrates up to 300 GHz

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***Abstract* — The attenuation constant of coplanar waveguide (CPW), conductor backed CPW (CBCPW) and grounded CPW (GCPW) interconnects is compared up to 300 GHz. Spin-on benzocyclobutene (BCB) dielectric is deposited on low resistivity (10 Ω-cm) silicon (Si) substrates to characterize the loss of interconnects at millimeter-wave (mm-wave) frequencies. CPW fabricated on 58 µm of BCB has similar performance as CBCPW and GCPW fabricated on 8.5 µm and 7.6 µm of BCB, respectively. CPW with thick dielectric layers present attenuation of 1.89 dB/mm at 300 GHz, whereas CBCPW and GCPW have an attenuation of 1.87 dB/mm and 1.96 dB/mm, respectively, at the same frequency.**

Index Terms — Attenuation constant, BCB, CBCPW, CPW, GCPW, mm-wave.

I. INTRODUCTION

The millimeter-wave (mm-wave) frequency band is specified from 30 – 300 GHz, with a corresponding free space electrical wavelength of 10 to 1 mm [1]. At those high frequencies and short wavelengths, distributed circuit elements are significantly reduced in size. Silicon (Si) technologies such as deep submicron complementary metal oxide semiconductor (CMOS), bipolar (Bi) CMOS and silicon germanium (SiGe) have found more and more acceptance in microwave and mm-wave integrated circuits (ICs) because of their advantages of low cost, reduced size, high yield, and system-on-chip performance [2]. The on-chip integration performance is limited by passives and transmission line (TL) interconnects, which are essential to connecting different blocks of RF circuits (e.g. low noise amplifiers, local oscillators, mixers, power amplifiers) [3]. In this paper we present results of coplanar interconnects that can be used to integrate planar radiators with CMOS ICs using thin-film processing techniques.

Mm-wave interconnects are typically designed using microstrip lines, coplanar waveguides (CPWs), or finite ground CPWs (FGCPWs), as they provide compact, planar, and low loss solutions [4]. In Si technology, the CPW experiences the highest loss primarily due to the presence of the low resistivity (ρ = 10 – 20 Ω-cm) Si substrate underneath it. However, it is the easiest to fabricate with no via requirements and the ground plane being on the same plane as the center conductor. CPW provides flexibility in design compared to microstrip by allowing the signal width and ground plane gaps to be varied to optimize impedance and attenuation [5]. Conductor backed CPW (CBCPW) and grounded CPW (GCPW) both have a bottom ground plane that shields the Si substrate and eliminates the substrate loss mechanism [6]. In CPW, the field interaction with the Si substrate can be reduced by the use of insulators that separate the metal from the substrate [7-9]. Substrate interactions with TLs are reduced by applying low loss tangent ($tan\delta$), and low permittivity (ε_r) dielectric layers with thicknesses typically greater than 10 µm on top of a low-resistivity Si substrate [5], [10]. Thick dielectric layers have been introduced in literature with an average height of 20 µm that reduce the loss in CPW to reasonable values. As design frequencies increase beyond 100 GHz, the dielectric thickness will need to increase or an alternative process will be required. We investigate the use of (i) GCPW, (ii) dielectrics thicker than 20 µm, and (iii) CBCPW, with and without, slots to mitigate loss. For the first time we show the measured results up to 300 GHz. Attenuation is compared for benzocyclobutene (BCB), parylene-N, cyclic olefin copolymer (COC) and polyimide at 40 and 220 GHz.

This paper presents the mm-wave performance of three CMOS interconnects: CPW, CBCPW, and GCPW fabricated on low loss BCB dielectric. Section II shows the performance of CPW on the thick dielectric. Section III demonstrates the performance of CPW with multi-layer BCB. Section IV discusses CBCPW and GCPW and Section V draws the conclusion.

II. CPW ON THICK DIELECTRIC

The CPW interconnect is designed by a signal conductor of width, w, separated by a gap (g) from a pair of ground conductor of finite width (w_g), all on the same plane. Conductors are patterned on top of a dielectric layer of thickness h_d which is deposited on top of the Si substrate of thickness h_s. The cross section of the CPW is shown in Fig. 1, where metal thickness is described by t_{top}.

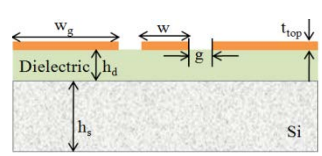

Fig. 1. Cross-section of a CPW interconnect.

Table I and Table II show the substrate properties and total attenuation of CPWs on thick dielectric layers at 40 GHz as reported in the literature. For an average thickness of 20 µm, the attenuation ranges from 0.3 to 0.56 dB/mm. By removing the polyimide between gaps, the loss is further reduced to 0.275 dB/mm [9]. We have similarly deposited 24 µm of BCB and measured loss of 0.47 dB/mm.

Table I
Thick polymer dielectric and Si property

Ref.	Dielectric	ε_r	$tan\delta$	$\rho(\Omega$ -cm)
[7]	PI-2611	3.12	0.002	15.6
[8]	DuPont WE1111	2.8	0.0018	1 - 20
[9]				1
[10]	Parylene-N	2.35- 2.4	0.0006	10
[12]	Cyclotene 4026-46	2.65	0.002	10
This work	Cyclotene 4024-40	2.65	0.002 [13-14]	10

Table II
Measured attenuation (α) (dB/mm) at 40 GHz

Ref.	Interconnect	h_d (µm)	t_{top} (µm)	α
[7]	FGC	20	1.5-Au	0.4
[8]	CPW	20.15	1.5-Au	0.55
[9]	µ-CPW	20.15	1.5-Au	0.275
[10]	CPW	15	3.5-Au	0.56
[12]	FGCPW	21	5-Cu	0.3
This work	CPW	24	1-Au	0.47

III. CPW on Thick BCB

50 Ω CPW lines of several lengths (0.5, 2, 3 and 4 mm) have been fabricated on a 10 Ω-cm, 500 µm thick CMOS grade Si wafer using multiple BCB layers. The attenuation constant (α) of 4 mm long lines is calculated from measured S-parameters [15] and shown in Fig. 2 up to 325 GHz. Attenuation decreases from 6.5 dB/mm to 1.89 dB/mm at 300 GHz for BCB thicknesses of approximately 7.5 times. The low frequency loss approaches its minimum value when 24 µm of dielectric is deposited.

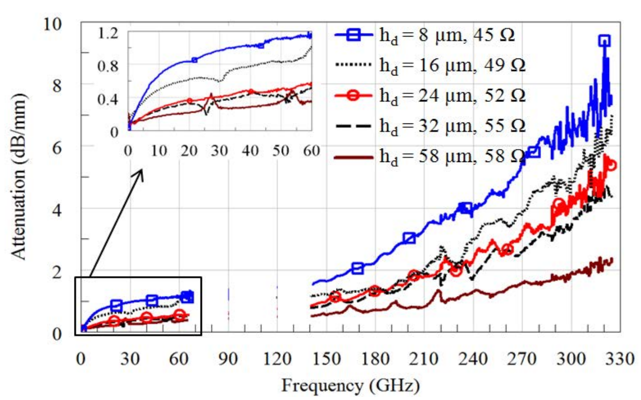

Fig. 2. Measured attenuation of CPW fabricated on multi-layer BCB.

IV. CBCPW and GCPW

The addition of a bottom ground in CPW shields the lossy Si substrate and improves the attenuation at mm-wave frequencies. CBCPW is formed when a ground plane is placed on the opposite side of the dielectric [11]. As the bottom ground is not connected to the top grounds it is also referred to as floating ground CPW (FGCPW). This floating ground can be a solid sheet or it can be slotted with slot width (w_s) and slot spacing (s_s) as shown in the Fig. 3 inset. The performance of slotted ground CPW (SGCPW) is compared with CPW fabricated on the same substrate up to 67 GHz in Fig. 3. Slots reduce CPW loss by approximately 0.4 dB with width and spacings of 10 µm performing better than 25 µm. Table III compares their performance at 50 GHz. The GCPW reported by [16] shows that a solid ground plane produces 0.38 dB/mm loss at 50 GHz as shown in Table III.

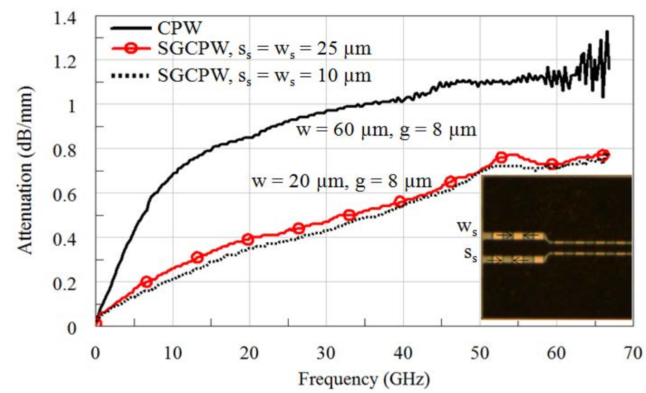

Fig. 3. Measured attenuation of CPW and SGCPW fabricated on 6.6 µm of BCB.

Table III
Measured attenuation (α) (dB/mm) at 50 GHz

Interconnect	h_d (µm)	$Z_0(\Omega)$	α	Ref.
CPW	6.6-BCB	45	1.1	This work
SGCPW	6.6-BCB	52	0.7	This work
GCPW	8.4-COC	50	0.38	[16]

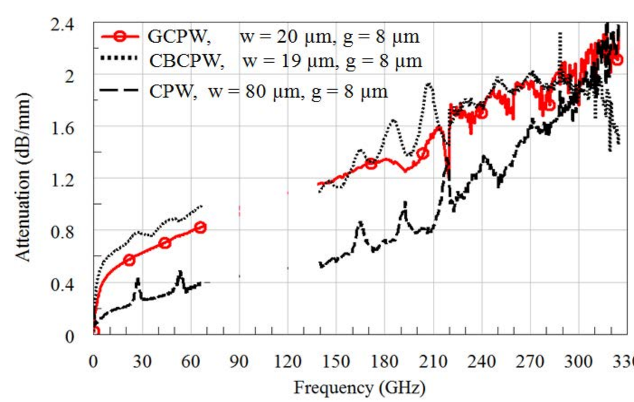

Fig. 4. Measured attenuation of CBCPW, GCPW fabricated on approximately 8 µm of BCB and CPW fabricated on 58 µm of BCB.

In GCPW fabrication the bottom ground is connected with the top using vias through the dielectric [11]. Fig. 4 shows the attenuation of CBCPW and GCPW fabricated on a single-layer of BCB, in comparison with CPW on thick BCB. CBCPW and GCPW have similar performance, although there is approximately 1 µm BCB thickness variation between them. GCPW is processed on 7.6 µm of BCB having a measured impedance of 45 Ω, whereas CBCPW on 8.5 µm of BCB has an impedance of 55 Ω at 60 GHz. The measured attenuation at 220 and 300 GHz along with their dimensions is listed in Table IV.

Table IV
Measured attenuation (α) (dB/mm) of Interconnects

Interconnect	h_d (µm)	Au (µm)	α 220	α 300	Ref.
CBCPW	8.5-BCB	0.75	1.6	1.87	This work
GCPW	7.6-BCB	1.0	1.6	1.96	This work
CPW	58-BCB	1.2	1.0	1.89	This work
GCPW	22-COC	1.0	0.6	-	[16]
Microstrip	20-BCB	3.0	0.6	-	[17]

It is noticeable from Fig. 4 that CPW on 58 µm BCB performs better than CBCPW and GCPW on approximately 8 µm BCB over the wide frequency band up to 300 GHz. CPW performance can be further improved by using a slotted ground or solid ground underneath the BCB. GCPW on thick polymer would perform the best as indicated by work in [16], but it requires additional via processing during fabrication. SGCPW or CBCPW does not require vias. By using a combination of multi-layer processing and a floating bottom metal, one can mitigate the loss of CPW at mm-wave frequencies.

V. Conclusion

CPW interconnects fabricated on thick layers of BCB and CBCPW and GCPW fabricated on a single-layer of BCB have been compared up to 300 GHz for the first time. CPW with BCB thicknesses of 58 µm has better performance than CBCPW and GCPW at 220 GHz. The CPW fabricated on 58 µm BCB has similar attenuation (α = 1.9 dB/mm) as CBCPW and GCPW at 300 GHz. BCB deposition is compatible with thin-film processing and can be used for mm-wave packaging and on-chip integration.

Acknowledgements

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