Indian Journal of Engineering & Materials Sciences
Vol. 30, February 2023, pp. 132-137
DOI: 10.56042/ijems.v1i1.60343

RF and Crosstalk Characterization of Chip Interconnects Using Finite Element Method

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Received: 11 February 2022; Accepted: 28 November 2022

This paper presents new finite element method (FEM) based approach for radio frequency (RF) and crosstalk (X talk) characterization of chip interconnects. Being based on scattering parameters (S-parameters), this approach truly and accurately demonstrates the transmission line behavior of chip interconnects over a wideband of frequencies. To demonstrate FEM based method, a single-line and a 3-line interconnect test structures on SiO2-Si substrate have been designed and simulated in High Frequency Structure Simulator (HFSS). The RF and crosstalk characterization of chip interconnect materials Copper (Cu), doped multilayer Graphene Nanoribbon (DMLGNR), and neutral multilayer Graphene Nanoribbon (NMLGNR) have been demonstrated in terms of transmission coefficient $\left(S_{ij} \,\&\, S_{mn}\right)$ from 1 to 1000 GHz. The single-line three-dimensional (3D) structures comprising of Cu, DMLGNR, and NMLGNR have maximum transmission loss values of -15.93 dB, -22.03 dB, and -13.73 dB at frequencies of 643 GHz, 402 GHz, and 643 GHz, respectively whereas three-line bus structure exhibit maximum victim-line transmission loss values of -15.28 dB, -17.47 dB, and -15.98 dB at frequencies of 247 GHz, 829 GHz, and 377 GHz, respectively. Further, the crosstalk results have demonstrated that as frequency increases significant crosstalk is observed between nearby lines due to electromagnetic interference and coupling (EMI/EMC) issues.

Keywords: Crosstalk, EMI, EMC, Finite Element Method, HFSS, IC

1 Introduction

The chip interconnects have started becoming more critical bottleneck in overall system performance at Gigahertz frequencies[1]. The signal integrity degradation due to higher packing density, dielectric imperfections, EMI/EMC issues and skin effect etc., have started worsening at higher frequencies and could not be omitted in modern integrated circuits[1] (ICs). In this context, the overall system performance has become greatly a function of chip interconnects as compared to logic devices on an IC. So, the necessity of accurate RF performance characterization of chip interconnects has arisen in modern ICs. There are broadly two types of approaches namely time domain and frequency domain[2]. In time domain, the electrical performance of interconnects has been generally measured in terms of propagation delay, power dissipation and eye diagrams while in frequency domain it is measured in terms of transfer function, 3-dB bandwidth and S-parameters. Due to emerging requirements of modern ICs to operate at very high data rates, the chip interconnect can be modeled as transmission lines[2-3](TLs).

Due to dielectric loss, proximity effect, and skin effect issues, the TLs fabricated on a low-loss silicon substrate have started to exhibit variation in frequency-dependent characteristics[4]. Researchers have been trying to develop fast and precise techniques for determination of performance metrics of chip interconnects and packaging modules. The problem is not as simple as it appears mainly due to electromagnetic modeling related complications. Modern day ICs operate at GHz frequencies, contain 12 to 25 layers of metal, very high device packing density and complexity. These complex IC shave multichip modules (MCMs) to minimize delay and crosstalk. TLs act as basic interconnecting entities in ICs and MCMs. They have been generally characterized with distributed circuit parameters which determine their behavior and performance in complex ICs[5]. The full-wave characterization techniques make use of direct discretization of Maxwell's equations to determine a numerical solution for all frequencies[5]. They have ideal choice for accurate RF characterization of TL structures.

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It is important to investigate the transmission line behavior of interconnects on silicon-silicon oxide (Si-SiO2) structure a default for most of real-time ICs. It has been reported that conductance of Silicon substrate lead to inductive and capacitive couplings in the structure. The conducting silicon substrate has capacitive and inductive coupling effects in the structure. In literature, several methods have been reported for RF characterization of chip interconnect materials. A new microwave circuit theory has been introduced using the concept of negative group-delay (NGD) for a three parallel interconnect line topology. The three parallel interconnect lines have been represented by distributed microstrip lines. S-parameters have been extracted from general admittance matrix and NGD theory is developed using them[4]. The transmission parameters of on chip structures have been extracted from S-parameter[5]. A new TL characterization technique has illustrated for lossy chip interconnect lines of ICs[6]. The influence of modified skin effect model along with S-parameters have been considered in modeling frequency dependence of TLs. A precise methodology for chip interconnects developed from experimental results has been introduced which permits equivalent circuit model selection, parameter extraction, and determination of number of subsections of circuit[7]. S-parameter techniques for analysis of chip interconnects have been implemented and investigated. A new algorithm has been introduced with multiport interconnect capabilities in addition to the existing S-parameter network analysis framework[8]. Incremental extrapolation of S-parameters based computationally-efficient wide-bandwidth characterization method for arbitrary interconnect structures has been demonstrated[9]. The method can accomplish multistep deductions for segments of interconnects having specified interconnect lengths, widths, spacings, metal layers, and nearby routing details. Finite difference time domain (FDTD) and finite element methods have been used to investigate 4 types of discontinuities in interconnect structures[10]. A new signal transient characterization method based on S-parameters has been presented for chip interconnects which could generate precise information about signal integrity verification[11].

In this work, finite element method approach for RF characterization and crosstalk analysis of emerging chip interconnect materials has been presented. The emerging carbon based nanointerconnect materials have been chosen for FEM analysis. Graphene nanoribbon (GNR) a carbon based nanointerconnect material has multiple advantages of having planar structure, easy to fabricate, and large momentum relaxation time etc.[12-13]. However, many researchers have reported that neutral GNRs are not good candidates for intermediate and global level chip interconnects. So, intercalation doping has been seen as perspective solution to enhance conductivity, mean free path (MFP) and Fermi energy[14-17]. The interconnect materials have been analyzed using FEM approach are Copper, neutral and intercalated multi-layer Graphene nanoribbons (MLGNR).

This paper presents FEM based approach for RF and crosstalk characterization of various chip interconnect materials. Section 2 describes the various materials and methods considered for study along with 3D test structures and the simulation set-up. Section 3 illustrates results and their discussion. The paper concludes with the conclusion in Section 4.

2 Materials and Methods

The material dependent parameters taken from experimental results[14-18] for this studyare listed in Table 1.

The 3-dimensional (3D) electromagnetic simulation tool High Frequency Structure Simulator[19] (HFSS) was used for S-parameter extraction of single-line and 3-line interconnect architecture-based 3D test structures were developed on a Si-SiO_2. HFSS used FEM numerical technique in which a test structure was divided into many sub-parts called finite elements. These finite elements were of tetrahedral shape. These tetrahedras develop a mesh of all finite elements. The tool generates solution for fields within the mesh. After finding the field solution, the tool derives the S-matrix from it. In modern ICs, interconnect lines could be modeled using microstrip

Table 1 — Material dependent parameters for interconnect materials under for study

Parameter (s)	Interconnect Materials		
	Copper (Cu)	Neutral-MLGNR	AsF_5 doped-MLGNR
Conductivity (μΩ-cm)-1	0.4545	0.026	0.63
Mean Free Path (nm)	40	419	1030
Momentum Relaxation time (s)	$2.55x10^{-14}$	$2.16\ x10^{-13}$	$5.3\ x10^{-13}$

line structures. We started constructing the test structure shown in Fig. 1 (a) with a metallic ground at the bottom, on top of the ground a silicon substrate layer is drawn, on top of the silicon substrate a layer of SiO_2 is drawn, finally on SiO_2 dielectric layer a microstrip line layer is laid. In this work, firstly FEM analysis of a single microstrip line on silicon oxide-silicon substrate is carried out. Secondly, a three-line bus structure shown in Fig. 1 (b) was designed and carried out in its FEM analysis. From FEM analysis, the S-parameters were extracted which present the RF and crosstalk characterization of single and three-line bus structures.

The geometrical parameters of the three-line bus structure are listed in Table 2. The length, width, and height of the single-line bus structure are kept the same as in Table 2.

The conductivity (σ_{Si}) of the silicon substrate is assumed to be 10 Siemens/m for all full-wave simulations of 3D structures. The solution type preferred for signal integrity-related simulations are generally *Driven Modal* type. The S-matrix output of TL modes is expressed in terms of incident/reflected powers. The electromagnetic fields i.e. excitation to the designed structures is given through ports in HFSS. The ports yield S, Z, Y, and fields report. Lumped ports are used for all structures as they are generally used to provide excitation in transmission lines.

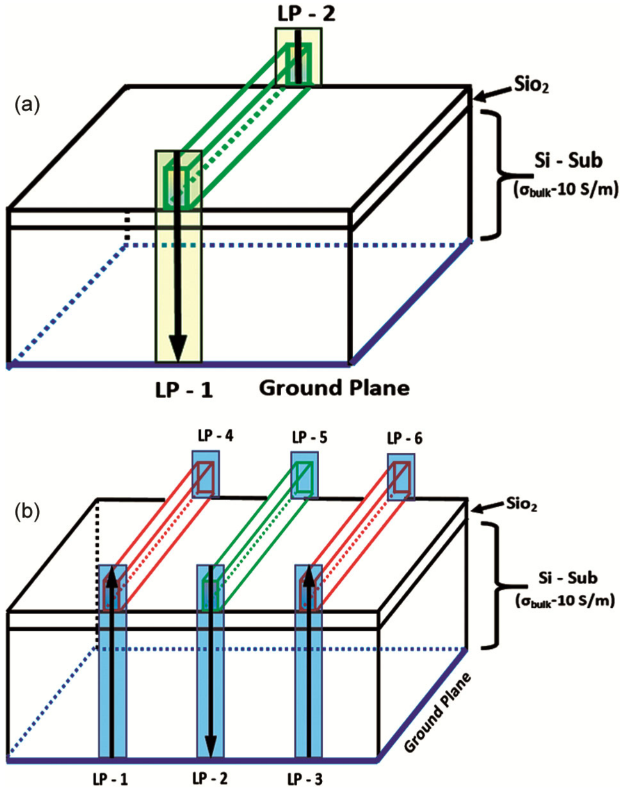

Fig. 1 — 3D structures used for extraction of S-parameters from FEM analysis to characterize RF and crosstalk behavior (a) Single-line structure, and (b) Three-line bus structure.

Table 2 — 3D geometrical parameters of three-line bus structure

Interconnect lines	Length (um)	Width (nm)	Height (nm)	Spacing (nm)
1, 2, 3	1000	21	63	200

3 Results and Discussion

RF and crosstalk measurement results are enumerated along with characterization. The interpolating frequency range in the full-wave simulator is varied from 1 GHz to 1 THz. The S-parameter data of single interconnect-line and three-line bus structures are extracted using HFSS. The transmission coefficients $\left(S_{ij} \,\&\, S_{mn}\right)$ and passivity associated with interconnect lines have been extracted from the structures using HFSS. Here, the S_{ij} represents transmission loss or insertion loss experienced by the signal while flowing through an interconnect-line. The S_{mn} denoted transmission coefficient between the nearby wires. It basically characterized the degradations caused by EMC/EMI effects on the signals propagating through nearby interconnect-lines.

The Fig. 2 illustrated transmission loss $\left(S_{21}\right)$ of Cu, NMLGNR, and DMLGNR interconnect materials for a length of 1000 μm.

It reflected transmission loss occurring in transmission of EM power from input port-1 to output port-2. The signal loss is minimum below 200 GHz

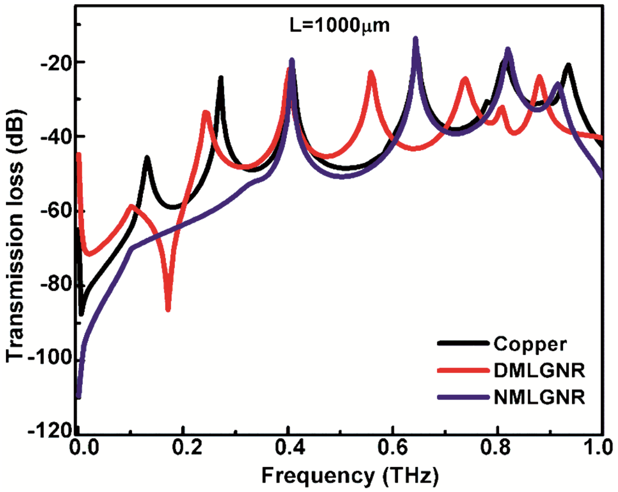

Fig. 2 — Transmission loss characteristics of single-line 3D interconnect structure extracted from FEM analysis for different interconnect materials.

for all materials and starts increasing significantly fast above 200 GHz. The waveforms explicitly reflect that signal loss degradation increases with an increase in frequency which results in signal integrity issues influencing the RF performance of interconnect lines. The Cu, DMLGNR, and NMLGNR have maximum transmission loss values of -15.93 dB, -22.03 dB, and -13.73 dB at frequencies of 643 GHz, 402 GHz, and 643 GHz, respectively. Similarly, the Cu, DMLGNR, and NMLGNR have minimum transmission loss values of -87.61 dB, -71.31 dB, and -109.43 dB at frequencies of 6 GHz, 26 GHz, and 1 GHz, respectively. The maximum and minimum transmission loss differences between Cu and DMLGNR are 27.3 dB at 643 GHz and -23 dB at 6 GHz, respectively. The maximum and minimum transmission loss differences between Cu and NMLGNR are 44.4 dB at 1 GHz and -3.74 dB at 909 GHz. Similarly, maximum and minimum transmission loss differences between DMLGNR and NMLGNR are 64.6 dB at 1 GHz and -29.5 dB at 643 GHz, respectively. The Fig. 3 illustrates the transmission loss (S_{21}) of a three-line bus structure in aggressor-victim-aggressor (*agg-vic-agg*) configuration.

Figure 3 (a, b, & c) illustrates the transmission loss of Cu, DMLGNR, and NMLGNR in *agg-vic-agg* configuration for the length of 1000 µm. The direction of electric field on the victim line is set opposite to the aggressors. Fig. 3 (d) represents victim-line transmission loss of Cu, DMLGNR, and NMLGNR.

The Cu, DMLGNR, and NMLGNR have maximum victim-line transmission loss values of -15.28 dB, -17.47 dB, and -15.98 dB at frequencies of 247 GHz, 829 GHz, and 377 GHz, respectively. Similarly, the Cu, DMLGNR, and NMLGNR have minimum victim-line transmission loss values of -82.94 dB, -62.6 dB, and -104.29 dB at frequencies of 6 GHz, 11 GHz, and 11 GHz, respectively.

The Fig. 4 describes the transmission loss difference experienced by victim-line of various interconnect materials. The maximum difference observed is between DMLGNR and NMLGNR while minimum difference is between Cu and NMLGNR.

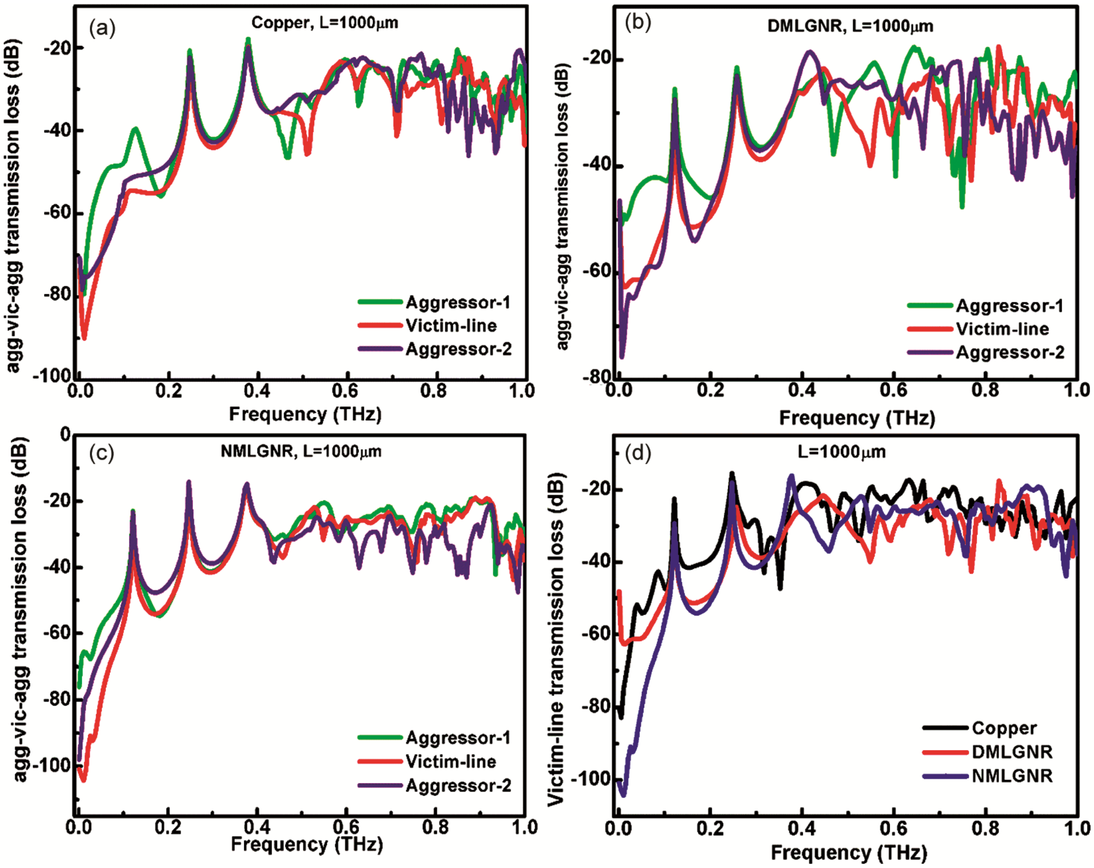

Fig. 3 — (a-d) Transmission loss characteristics of three-line bus structure extracted from FEM analysis at L=1000µm for (a) Copper (b) DMLGNR (c) NMLGNK and (d) Comparisor of transmission loss characteristics of Copper, DMLGNR and NMLGNR.

The three-line bus structure of Fig. 1 (b) is used to study the crosstalk behaviour of different types of interconnect materials viz. Cu, DMLGNR, and NMLGNR for a global interconnect length of 1000 µm. The S-parameters (S_{12}), (S_{23}) and (S_{13}) are also extracted from the FEM analysis. The S-parameters (S_{12}), (S_{23}) and (S_{13})represent the crosstalk between interconnect line 1 and 2, 2 and 3, and 1 and 3, respectively. The Fig. 5 (a) depicts the crosstalk between interconnect lines 1 and 2, Fig. 5 (b) between 2 and 3, and Fig. 5 (c) depicts the crosstalk between 1 and 3, respectively. The waveforms explicitly indicate that as the frequency increases, crosstalk starts increasing significantly owing mainly due to EMC/EMI effects.

It is observed that in all types of chip interconnect materials i.e. Cu, DMLGNR, and NMLGNR, the s-parameters S_{12} and S_{23} characterizing the crosstalk between lines saturate above 100 GHz value around value of -5 dB. The fall in crosstalk parameter S_{12} is reported between 523 GHz and 608 GHz for Cu and between 764 GHz and 784 GHz in case of DMLGNR. Similarly, in case of crosstalk parameter S_{23} the dip is only observed for Cu only between 337 GHz and 427 GHz. In case of crosstalk parameter S_{13}, reduced crosstalk is observed as the spacing between lines 1 and 3 is 2 times than between lines 1 and 2, and 2 & 3, respectively. The value of S_{13} gets almost saturates around 397 GHz at an approximate value of -10 dB for DMLGNR and NMLGNR interconnects. Slightly reduced crosstalk is observed for Cu based interconnect lines. Also, it is seen that there are noticeable falls in crosstalk for Cu and DMLGNR materials between 337 GHz and 387 GHz, and 774 GHz and 854 GHz, respectively. So, it can be concluded that by increasing the spacing between lines, significant reductions can be achieved in crosstalk. The results also reveal that Cu interconnects are slightly better in the context of crosstalk than neutral and doped MLGNR interconnects.

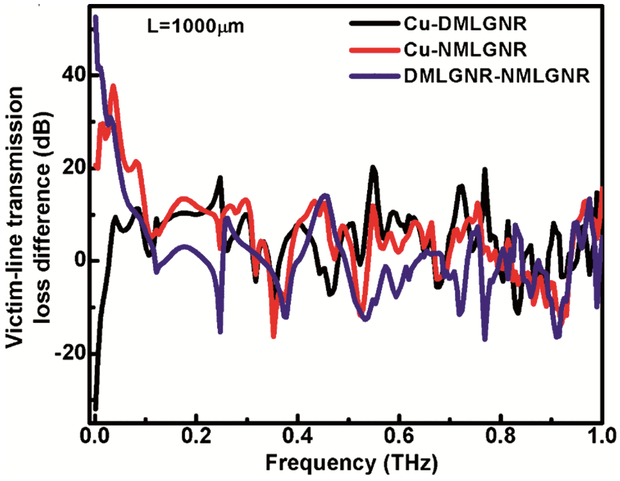

Fig. 4 — Victim-line transmission loss difference of three-line bus structure extracted from FEM analysis.

The passivity characteristics of different interconnect materials have been also reported over a wide band of frequencies. Any interconnect structure by default dissipates active power for any input voltage and frequency. Hence, the computed S-parameters from any structure must exhibit passive behaviour. Equation (1) is used to determine the value of passivity as

$$P = I - \text{Conjugate}(\text{transpose}(S)) \qquad \ldots(1)$$

where, P is the passivity matrix, I is the identity matrix and S is the S-parameter matrix. The condition is that S must be a positive semi-definite matrix having only non-negative values. The passivity simulations calculate eigenvalues of the passivity matrix P. The default value of passivity is 1.0 in magnitude. Figure 6 enumerates the passivity characteristics of Cu, DMLGNR, and NMLGNR

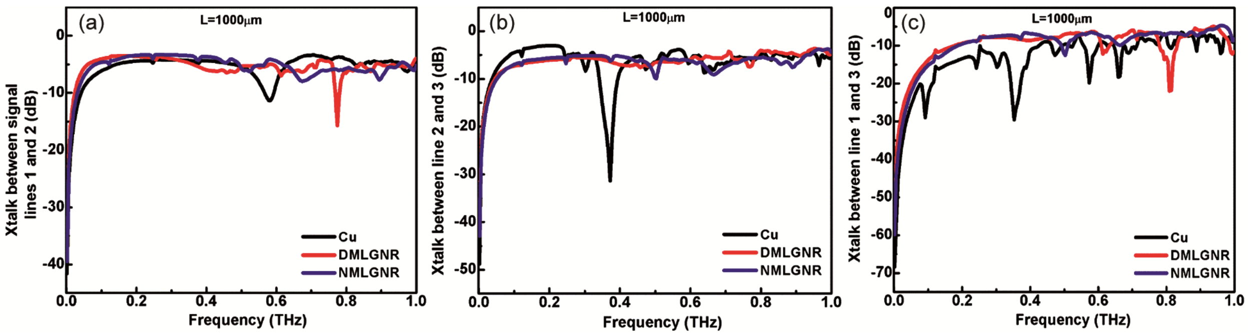

Fig. 5 — Crosstalk characterization between lines (a) 1 and 2, (b) 2 and 3, and (c) 1 and 3.

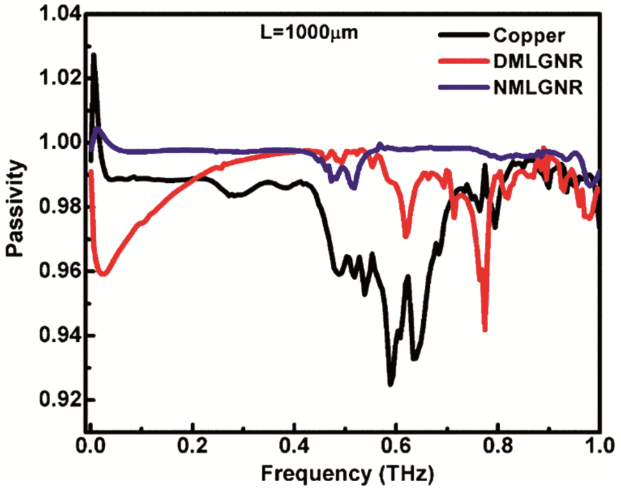

Fig. 6 — Passivity characteristics of various interconnect materials.

interconnect materials. The DMLGNR material exhibit close to the ideal value of 1 whereas Cu and NMLGNR exhibit significant variations in passivity behaviour over a wide band of frequencies.

4 Conclusion

An accurate FEM analysis approach is presented for RF and crosstalk characterization of chip interconnect lines. Two 3D test structures on SiO_2.Si substrate have been designed and simulated in HFSS to extract the desired S-parameters of interest. The RF and crosstalk characterization of chip interconnect materials Cu, DMLGNR, and NMLGNR is demonstrated in terms of S-parameters for a wide frequency range of 1 to 1000 GHz. The RF results explicitly reflect that signal loss degradation increases with an increase in frequency which results in signal integrity issues at higher frequencies due to EMI/EMC issues. Further, the passivity results were extracted for the proposed test structure and observed that DMLGNR demonstrates DMLGNR material exhibit close to the ideal value of 1 whereas Cu and NMLGNR exhibit significant variations in passivity behaviour over a wide band of frequencies. The passivity results suggests that DMLGNR material could be the ideal choice for chip interconnects.

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