Comparative radio-frequency and crosstalk analysis of carbon-based nano-interconnects

Manjit Kaur1 | Neena Gupta1 | Sanjeev Kumar2 | Balwinder Raj3 | Arun K. Singh1

1Department of Electronics and Communication Engineering, Punjab Engineering College (Deemed to be University), Chandigarh, India
2Department of Applied Sciences, Punjab Engineering College (Deemed to be University), Chandigarh, India
3Department of Electronics and Communication Engineering, National Institute of Technical Teachers Training & Research, Chandigarh, 160012, India

Correspondence
Arun K. Singh, Department of Electronics and Communication Engineering, Punjab Engineering College (Deemed to be University), Chandigarh, India-160012.
Email: arunkumar.singh@outlook.com

Abstract
A comparative radio-frequency (RF) and crosstalk analysis is performed on carbon nano-interconnects based on an efficient \( \pi \)-type equivalent single-conductor model of bundled multwall carbon nanotubes (MWCNTs) and stacked multilayer graphene nanoribbons (MLGNRs). Simulation results are extracted using HSPICE for global-level nano-interconnects at the 14-nm node. RF performance is evaluated in terms of skin depth and a 3-dB bandwidth, while crosstalk performance is analysed in terms of crosstalk-induced delay and average power consumption. The skin-depth results indicate significant improvements in skin-depth degradation at higher frequencies for AsF\(_3\)-doped zig-zag MLGNRs compared with that of Cu, nanotubes and MWCNTs. The transfer gain results explicitly demonstrate that AsF\(_3\)-doped MLGNRs exhibit excellent RF behaviour, showing 10- and 20-fold improvements over MWCNTs and copper (Cu), respectively. Further, the 3-dB bandwidth calculations for AsF\(_3\)-doped MLGNRs suggest 18.6- and 9.7-fold enhancement compared with Cu and MWCNTs at 1000 \( \mu \)m. Significant reductions are obtained in crosstalk-induced out-of-phase delays for AsF\(_3\)-doped MLGNRs—their delay values were 84.7% and 60.24% less than those for Cu and MWCNTs. Further, AsF\(_3\)-doped MLGNRs present the most optimal energy-delay product results, with values representing 98.6% and 99.6% improvements over their Cu and MWCNT counterparts at a global length of 1000 \( \mu \)m.

1 | INTRODUCTION

Chip interconnects integrate wiring systems accounting for the distribution of clock, power, ground, input/output and other control signals as one of the various functional blocks and systems of interconnects [1]. The International Technology Roadmap for Semiconductors (ITRS) emphasises the performance evaluation of new, emerging nanomaterials as replacements for copper (Cu) in chip interconnect applications. The most stringent performance goal for interconnects is to meet high-bandwidth low-power signalling requirements with continued scaling with no bottlenecks [1]. The requirements are becoming more stringent for propagation delay and power consumption as well. At present, the interconnect bottleneck has been impending mainly at a global level due to longer wires that do not scale down according to silicon feature size, which results in a high resistance–capacitance (RC) issue. The RC issue could be addressed to some extent with the introduction of repeaters to minimise the quadratic effect of RC delay at the expense of a greater silicon area and higher power consumption [1]. Therefore, serious issues have begun to emerge at the end of the interconnect road map that are driving the need to evaluate futuristic interconnect technologies as replacements for existing Cu/low-\( \kappa \) technology [1]. Carbon-based nanomaterials, namely carbon nanotubes (CNTs) and graphene nanoribbons (GNRs), have fuelled major research interest as futuristic chip interconnect materials owing to their novel attributes: higher mean free path (MFP), current-carrying capability, thermal conductivity, mechanical strength, pattermability to nanoscale etc. [2–7].

Only a few researchers [8–11] have conducted radio-frequency (RF) analysis of multilayer graphene nanoribbon (MLGNR) and multwall carbon nanotube (MWCNT) interconnects. The high-frequency behaviour of neutral and doped MLGNRs has been investigated in terms of skin-depth and surface impedance parameters [8,9]. That paper lacks...
validation of RF behaviour at the circuit level. The relative stability of Cu, top-contact and side-contact MLGNRs has been analysed based on Bode plots [10]. The scope of that paper is restricted to local- and intermediate-level neutral MLGNR interconnects only. Furthermore, the choice of RF performance indicators is not sufficient. A research study compared MLGNRs and MWCNTs in terms of absolute transfer function and bandwidth using a driver-interconnect-load (DIL) system [11].

Crosstalk analysis of MWCNTs has been carried out; it compared ternary logic circuits utilising a five-line bus architecture considering both passive and active shielding [12]. The viability of the proposed shielding technique for standard binary logic is not discussed. Crosstalk analysis of coupled interconnects implementing alpha-power law model-based complementary metal-oxide semiconductor (CMOS) drivers using SPICE and an analytical model with a comparison of crosstalk noise results is reported in Ref. [13]. Crosstalk noise peaks are calculated for the out-of-phase (OP) and in-phase (IP) switching of coupled interconnects using linear resistance drivers [14]. A precise model for dynamic crosstalk evaluation of on-chip wires driven by alpha-power law model-based CMOS drivers is introduced in Ref. [15]. The on-chip wires are modelled using a finite-difference time-domain (FDTD) technique. A novel unconditionally stable method has been formulated to calculate peak crosstalk noise voltage and noise width for coupled interconnects [16]. It is validated against HSPICE and FDTD models. The crosstalk analysis of armchair and zigzag MLGNR interconnects was measured in terms of crosstalk-induced delay and noise for different types of repeater insertions using a three-line bus architecture [17]. A study based on a three-line coupled MLGNR interconnects demonstrates that they suffer less from crosstalk effects than MWCNTs and Cu counterparts [18]. A transmission line model of MLGNR interconnects has been introduced and analysed in terms of signal propagation and current distribution for radio frequencies up to 100 GHz [19]. An efficient and precise \( \pi \)-type multiconductor transmission line (MTL) model for rough-edged multilayered GNRs and bundled multivalved CNTs is proposed in [20] along with a simplified \( \pi \)-type equivalent single-conductor (ESC) model derived from it. On-chip interconnects have begun to encounter many problems at design, process and reliability levels. Major issues have started to appear at a global level for Cu interconnects. As MLGNRs and MWCNTs are foreseen as futuristic choices to replace Cu as interconnect materials, it is crucial to evaluate their RF and crosstalk performance for global-level interconnects using a comprehensive approach. In [5–20], RF and crosstalk analyses of MLGNRs and MWCNTs are presented. However, the scope of results is confined to one or two parameters in most cases and only for local- and intermediate-level interconnects. Herein, we highlight the comparative RF behaviour of futuristic carbon-based nano-interconnects within a broader set of RF-centric parameters for global-level interconnects. We also consider doped MLGNRs, as they do not suffer from higher resistivity and offer many advantages. Our results are based on a broader set of RF-centric parameters and experimental values used in the calculation of various material-dependent parameters. Further, 3-dB bandwidth is used to characterise the highest frequency to which a circuit will operate reliably.

The paper is organised as follows. In Section 2, various mathematical equations are used to calculate the resistor–inductor–capacitor (RLC) parameters of the equivalent \( \pi \)-type MTL and ESC models that are illustrated. Section 3 illustrates the RF behaviour of carbon-based nano-interconnects. Section 4 discusses the crosstalk analysis of different types of interconnect materials based on a three-line bus structure. Section 5 briefly presents transient results in terms of delay and energy-delay products (EDPs). Section 6 concludes and addresses the results.

## 2 | INTERCONNECT MODEL

The proposed interconnect structures for the bundled MWCNT and MLGNR interconnects are shown in Figure 1. The equivalent \( \pi \)-type MTL RLC model [20] of bundled MWCNT and MLGNR is shown in Figure 2a. This \( \pi \)-type MTL model provides approximately 29% and 6.5% reductions in delay over the L and T type models, respectively [20]. The simplified \( \pi \)-type ESC model shown in Figure 2b has been derived from the MTL model with a deviation of just 4.6%. This ESC model is used in DIL configuration for all SPICE simulations results reported here [20]. The mathematical expressions for resistances, inductances, and capacitances of bundled MWCNT and MLGNR interconnects can be derived from ESC models. A typical MWCNT consists of numerous concentric cylindrical shells placed parallel to one another with a Van der Waals gap between adjacent graphene shells of (\( \delta \approx 0.34 \text{ nm} \)) [21,22]. In the case of MLGNR, a typical interconnect model consists of numerous layers of graphene sheets.
FIGURE 2 (a) An equivalent π-type multiconductor transmission line resistor–inductor–capacitor model for bundled multiwall carbon nanotubes and multilayer graphene nanoribbons, and (b) a simplified equivalent single-conductor model derived from the multiconductor transmission line model in driver-interconnect load configuration [20].

2.1 | Resistance model

The contact resistance ($R_c$) of MLGNR- and MWCNT-based interconnects is computed as in [12,24]:

$$R_c = \left[ \frac{N_{\text{shell}}}{N_{\text{layer}}} \right] \left[ \sum_{j=1} \left( R_{j,mc} + R_{j,q}/2 \right) \right]^{-1} \tag{3}$$

where $R_{j,q}$ and $R_{j,mc}$ are the quantum and imperfect metal contact resistances for the $j$th shell/layer, respectively. The value of $R_{j,mc}$ resistance is decided by the fabrication technology depending on various techniques used for the growth process of CNTs/GNRs. The $R_{j,mc}$ value ranges from a few kiloohms to hundreds of kiloohms [12,21,22].

Figure 2b illustrates the π-type ESC model derived from the MTL model [20] for MLGNR interconnects. In this work, we consider a value of 2 kΩ for all simulations [12,21,22]. The fundamental quantum resistance ($R_q$) of a single shell/layer is 12.94 kΩ for each conducting channel and is evaluated analytically [12,21] using Equation (4), as

$$R_{j,q} = \frac{b}{2e^2N_{ch,j}} = 12.94 \text{ kΩ} \tag{4}$$

Stacked on top of each other with the same Van der Waals interval spacing [23].

The shell count in MWCNT can be calculated as in [21,22]:

$$N_{\text{shell}} = 1 + \text{Int.} \left[ \frac{(D_{\text{max}} - D_{\text{min}})}{2\delta} \right] \tag{1a}$$

where $D_{\text{min}}$ and $D_{\text{max}}$ are the respective diameters of the inner- and outermost shells of MWCNT. Int. [.] specifies that only the integer part of the expression is considered.

Similarly, the layer count in MLGNR [18] can be estimated as

$$N_{\text{layer}} = 1 + \text{Int.} \left[ \frac{H}{\delta} \right] \tag{1b}$$

where $W$ and $H$ represent the width and thickness, respectively, of the interconnect structure. In accordance with the ITRS road map, thickness is taken as thrice the width ($H = 3W$) for global-level interconnects [1]. An aspect ratio ($H/W$) of 3 is considered for all types of interconnect materials.

Each shell diameter of the MWCNT is calculated as below [21]:

$$D_j = D_{\text{max}} - 2\delta(j-1) \text{ for } 1 \leq j \leq N_{\text{shell}} \tag{2}$$
where $h$ is the Planck's constant, $e$ is electronic charge, and $N_{ch}$ signifies the number of conducting channels.

The channel count in each shell/layer ($N_{ch}$) is computed [22,24] as

$$N_{ch} = \sum_{i=1}^{n_v} \left[ \left( e^{(E_i-E_f)/kT_R} + 1 \right) \right]^{-1} + \sum_{i=1}^{n_v} \left[ \left( e^{(E_i+E_f)/kT_R} + 1 \right) \right]^{-1}$$

where $E_i$ is the sub-band energy above/below the Fermi level $E_F$, and $T_R$ and $k$ denote temperature and the Boltzmann's constant, respectively. The terms $n_v$ and $n_c$ represent the respective valence and conduction sub-bands.

The p.u.l. scattering resistance ($r_{i,MWCNT}$) of MWCNT [22,25,26] is calculated using Equation (6a), as

$$r_{i,MWCNT} = \frac{12.94 \, k \Omega}{\sum_{j=1}^{N_{shells}} \lambda_{eff} N_{ch,j}}$$

where the p.u.l. scattering resistance ($r_{i,MLGNR}$) of a single layer of GNR [12,18] is calculated using Equation (6b), as

$$r_{i,MLGNR} = \frac{12.94 \, k \Omega}{N_{ch_i} \lambda_{eff}}$$

where $\lambda_{eff}$ represents the effective MFP.

The previous studies in [27–29] have suggested that substrate effects may significantly influence the Fermi energy. In addition, electron scattering in GNRs caused by rough edge, phonons, and defects influence the MFP [30]. In this work, typical effective MFP ($\lambda_{eff}$) values have been adapted from previous experimental studies [1,8,30–34]. In the case of MWCNT, irrespective of whether shells are semi-conducting or metallic, the MFP is always a function of shell diameter.

The effective MFP of each MWCNT shell is calculated [23] as ($\lambda_{eff} \approx 1000D_j$), where $D_j$ is the $j$th shell diameter of MWCNT. In this work, the $\lambda_{eff}$ has been calculated at room temperature ($T_R = 300$ K) for all materials.

The total resistance ($R_T$) of MWCNT/MLGNR [18,23,24] based interconnects can be estimated using Equation (7), as

$$R = 2R_c + r_s L$$

where $L$ denotes the interconnect length, $R_c$ is the lumped resistance, and $r_s$ is the distributed resistance.

### 2.2 Inductance model

The kinetic inductance p.u.l. of MWCNT/MLGNR interconnects is primarily owing to kinetic energy stored in each conducting channel [18,23] and calculated using Equations (8a,b):

$$L_{k-MWCNT} = \frac{b}{4 \, e^2 \, \psi_F \sum_{j=1}^{N_{shells}} N_{ch,j}}$$

$$L_{k-MLGNR} = \frac{b}{4 \, e^2 \, \psi_F \, N_{ch}}$$

where term $\psi_F (\approx 8 \times 10^5 \, m/s)$ denotes Fermi velocity.

The magnetic inductance p.u.l. in MWCNT/MLGNR [18,21] is calculated as

$$L_{m-MWCNT} = \frac{\mu_0}{2\pi} \cosh^{-1} \left( \frac{2T}{D_{max}} \right)$$

$$L_{m-MLGNR} = \frac{\mu_0 \, \mu_r \, T}{W}$$

where $\mu_r$ and $\mu_0$ are the permeabilities of material and free space, respectively. In the case of the MWCNT bundle, $T$ is the distance from centre of the bottommost MWCNT to ground plane, while in the MLGNR, $T$ is the height from ground plane.

As the value of magnetic inductance is negligible compared with kinetic inductance in carbon-based nano-interconnects, it is omitted for all simulations in this study.

### 2.3 Capacitance model

The capacitance in MWCNT/MLGNR comprises quantum ($C_q$) and electrostatic ($C_G$) capacitances. Electrostatic capacitance is mainly caused by electric field coupling between the lowest layer/shell and the ground plane. The equivalent quantum ($C_q$) capacitance for MWCNT [23] interconnects is determined using recursive approach as given in Equations (10a–c):

$$C_{ri} = C_{Q[i]}$$

$$C_{r[i]} = \left( \frac{1}{C_{r[j-1]}} + \frac{1}{C_{m[j-1]}} \right)^{-1} + C_{Q[i]}$$

where $j = 1, 2, 3, 4, \ldots N_{shells}$.

$$C_{q-MWCNT} = C_{r[N_{shells}]}$$

where

$$C_{Q[i]} = 2 \, N_{ch} \left( \frac{2 \, e^2}{b \, \psi_F} \right) \quad 1 < j < N_{shells}$$

$$C_{m[j]} = \left( \frac{2 \, \pi \, e}{\ln \left( D_{j+1}/D_j \right)} \right)$$

where $j = 1, 2, 3, 4, \ldots (N_{shells} - 1)$, and $C_m$ denote mutual capacitance among nearby shells of MWCNT [21,23].
The quantum ($C_{q\text{-MLGNR}}$) capacitance for individual layers of GNR [18] interconnects is determined using Equation (11), as

$$C_{q\text{-MLGNR}} = \left(\frac{4 \varepsilon^2}{b} \varphi F N_d\right)$$

The equivalent electrostatic ($C_{e}$) capacitance for MWCNT [23] and MLGNR [18] is computed using Equations (12a,b), as

$$C_{e\text{-MWCNT}} = \frac{2\pi e}{\cosh^{-1}(2T/D_{\max})}$$

$$C_{e\text{-MLGNR}} = \frac{e_o e_r W}{T}$$

where $e_r$ and $e_o$ are permittivities of material and free space, respectively.

The equivalent $r_{\text{esc}}$, $l_{k\text{-esc}}$, $c_{q\text{-esc}}$, and $c_{e\text{-esc}}$ parameters of $\pi$-type ESC model of MWCNT and MLGNR for interconnect of length $L$ are computed using Equations (13a–d) and (13e–h), respectively, as

$$r_{\text{esc}(\text{MWCNT})} = \frac{r_{\text{esc}(\text{MWCNT})} \cdot L}{N_{\text{MWCNT}}}$$

$$l_{k\text{-esc}}(\text{MWCNT}) = \frac{L \cdot l_{k\text{-esc}(\text{MWCNT})} \cdot L}{N_{\text{MWCNT}}}$$

$$c_{q\text{-esc}(\text{MWCNT})} = C_{q\text{-MWCNT}} \cdot N_{\text{MWCNT}} \cdot L$$

$$c_{e\text{-esc}(\text{MWCNT})} = C_{e\text{-MWCNT}} \cdot L$$

$$r_{\text{esc}(\text{MLGNR})} = \frac{r_{\text{esc}(\text{MLGNR})} \cdot L}{N_{\text{MLGNR}}}$$

$$l_{k\text{-esc}}(\text{MLGNR}) = \frac{L \cdot l_{k\text{-esc}(\text{MLGNR})} \cdot L}{N_{\text{MLGNR}}}$$

$$c_{q\text{-esc}(\text{MLGNR})} = C_{q\text{-MLGNR}} \cdot N_{\text{MLGNR}} \cdot L$$

$$c_{e\text{-esc}(\text{MLGNR})} = C_{e\text{-MLGNR}} \cdot L$$

where $N_{\text{MWCNT}}$ [21] and $N_{\text{MLGNR}}$ [18] are the number of MWCNTs in a bundle and layers in an MLGNR stack, respectively.

In previous work [35], the ESC model representation of MWCNT/MLGNR interconnect has been derived from MTL model. Further, the influence of mutual inductance and capacitance may be incorporated amongst the neighbouring shells/layers of MWCNT/MLGNR interconnects to improve accuracy. The $\pi$-type ESC model can further be extended to through-silicon-via structures for the performance evaluation by using the RLC models similar to given in [36–38]. Table 1 lists the interconnect parameters such as width, height, thickness, resistivity at local/intermediate and global levels along with minimum-sized inverter parameters such as equivalent driver resistance ($R_{dr}$), equivalent driver capacitance ($C_{dr}$), and equivalent load capacitance ($C_{l}$) at the 14-nm technology node adopted from the ITRS 2007 road maps [34].

The conductivity of MWCNT [4,22,23] and MLGNR [3,5] interconnects is analytically calculated using Equations (14a,b), as

$$\sigma_{\text{MWCNT}} = \left(\sum_{j=1}^{N_{\text{MLGNR}}} \frac{2e^2}{b} \cdot \left(\frac{\lambda_{\text{eff}}}{L + \lambda_{\text{eff}}}\right)\right) \frac{4 \cdot L}{(\pi \cdot D_{\max})}$$

$$\sigma_{\text{MLGNR}} = \left(\frac{2e^2}{b} \cdot N_{\text{MLGNR}} \cdot N_d \cdot \left(\frac{\lambda_{\text{eff}}}{L + \lambda_{\text{eff}}}\right)\right) \frac{L}{(W \cdot H)}$$

The conductivity of emerging carbon-based materials and Cu are plotted in Figure 3. The results suggest that at a width of 21 nm, AsF₃-doped MLGNR demonstrates the highest conductivity, while copper offers the lowest. The conductivity of MWCNT is slightly less than that of AsF₃-doped MLGNR.
while much improved over Cu and neutral MLGNR. Hence, only doped MLGNRs could yield enhanced conductivity compared with MWCNTs. The conductivity plots for MWCNTs at widths of 50 and 100 nm, respectively in Figure 3 are also shown for different interconnect lengths varying from 1 to 1000 µm. The conductivity of Cu is taken as 0.4545 (µΩ-cm)\(^{-1}\) after duly accounting for grain boundary and surface scattering as well as the presence of barrier layer issues [1,8].

3 | RADIO-FREQUENCY ANALYSIS

The unique attributes of carbon-based nanomaterials have attracted the attention of chip designers due to their pattern-ability to nanoscale aligned with scaling of silicon feature size. They are being considered as futuristic replacement materials for Cu for on-chip interconnects. Hence, the RF behaviour of carbon-based nanomaterials are important to be analysed. This section presents comparative RF analysis of MWCNTs and MLGNRs. The analysis has been performed in terms of skin-depth, transfer gain, and 3-dB bandwidth parameters.

3.1 | Skin-depth analysis

At RF, the current flowing through a conductor surface confines to the outer boundary and is called skin effect. The skin depth for GNRs and CNTs [8,9] can be computed using Equation (15),

\[
\delta = \delta' \sqrt{\left[1 + (\omega \tau)^2\right]} \ast \sqrt{\left[1 + (\omega \eta)^2\right] - (\omega \tau)}
\]

where \(\tau\) and \(\eta\) are the momentum relaxation time and angular frequency, respectively. The skin depth at lower frequencies is calculated [8,9] using Equation (16), as

\[
\delta' = \frac{1}{\sqrt{\omega \mu_0 \sigma}}
\]

In this work, skin depth is computed for copper, MWCNT, and neutral and doped MLGNR materials, as shown in Figure 4, by varying the frequency from 1 GHz to 1 THz. The results demonstrate that as frequency increases, skin depth decreases, as the effective conductor surface area conducting current is reduced in all materials. Material-dependent parameters such as conductivity, MFP, and momentum relaxation time are taken from experimental results [1,26–30].

MWCNT, AsF\(_3\)-doped MLGNR, neutral MLGNR, and copper suffer skin-depth reductions of 0.78, 1.90, 9.54, and 2.29 µm, respectively. Neutral MLGNR nanomaterials suffer maximum skin-depth degradation primarily due to their smaller conductivity, while MWCNT and AsF\(_3\)-doped MLGNR exhibit lesser degradations. The skin depth is basically dependent on the conductivity, MFP, and momentum relaxation time of the materials. The higher value of onset of skin-depth saturation indicates that AsF\(_3\)-doped MLGNRs will perform more efficiently at higher frequencies due to the higher MFP and momentum relaxation time as well as higher conductivity. Skin-depth variations for different interconnect materials are enumerated in Table 2 at frequency points of 1, 10, 100, 1000 GHz, respectively, at an interconnect length of 1000 µm.

In the case of MWCNTs, the onset of skin-depth saturation occurs much earlier due to larger momentum relaxation time and kinetic inductance compared with AsF\(_3\)-doped MLGNR as evident from Figure 4. Skin-depth saturation begins at 10 GHz in MWCNT and 300 GHz in AsF\(_3\)-doped MLGNR.

3.2 | Transfer gain analysis

The transfer gain can be used as an effective tool to analyse the RF behaviour of a system. It performs transformation from its input(s) to the output(s). We analyse the transfer gain-based RF performance of different interconnect materials. The transfer gain is computed in HSPICE based on the equivalent RLC circuit as depicted in Figure 2b. The frequency range is kept from 1 GHz to 1 THz. The plots for transfer gain for various interconnect materials are depicted in Figure 5. The plots demonstrate that AsF\(_3\)-doped MLGNR exhibits excellent transfer gain-based RF behaviour that is a more than 10-fold improvement over MWCNT and neutral MLGNR, whereas it is 20-fold better than Cu. The major reason for the improved transfer gain of AsF\(_3\)-doped MLGNR is its much lower scattering resistance (∼8 kΩ) than neutral MLGNR (∼82.7 kΩ), MWCNT (∼11.8 kΩ), and Cu (∼40.7 kΩ) at an interconnect length of 1000 µm. In addition, the kinetic inductance of MLGNR is much lower than that of MWCNT. The 3-dB bandwidth (\(f_{\text{max}}\)) results for various interconnect lengths from 100 to 1000 µm are calculated for different interconnect materials. The HSPICE computed results for
Table 2: Skin-depth variations for different types of interconnect materials

| Frequency (GHz) | Cu   | n-MLGNR | AsF₅-Doped MLGNR | MWCNT |
|----------------|------|---------|------------------|-------|
| 1              | 2.36 | 9.86    | 2.00             | 0.98  |
| 10             | 0.74 | 3.09    | 0.62             | 0.28  |
| 100            | 0.23 | 0.92    | 0.17             | 0.20  |
| 1000           | 0.023| 0.28    | 0.09             | 0.20  |

Abbreviations: Cu, copper; MLGNR, multilayer graphene nanoribbons; MWCNT, multiwall carbon nanotube.

3-dB bandwidth are plotted in Figure 6. The $f_{3dB}$ values of neutral MLGNR are 45.8 and 0.6 GHz at lengths of 100 and 1000 μm, respectively.

Cu exhibits $f_{3dB}$ values of 25.6 and 0.3 GHz, while MWCNT exhibits 41.6 and 0.6 GHz at 100 and 1000 μm lengths, respectively. The AsF₅-doped GNR demonstrates excellent $f_{3dB}$ values of 90 and 5.8 GHz at 100 and 1000 μm. The AsF₅-doped GNR demonstrates 3.5- and 18-fold enhancement in 3-dB bandwidth compared with Cu at 100 and 1000 μm, while compared with MWCNTs, the improvement is 2.1- and 9.7-fold, respectively. The 3-dB bandwidth results, therefore, clearly establish the superiority of AsF₅-doped MLGNR over other interconnect materials.

Table 3 depicts the 3-dB bandwidth at interconnect lengths of 100, 500, and 1000 μm for different interconnect materials analysed in this study.

4 | CROSSTALK ANALYSIS

Crosstalk is unwanted electromagnetic effect caused by a signal carrying wire on nearby wires. It originates due to presence of unwanted couplings in the form of conductive, inductive, and capacitive among the signal carrying wires. The capacitive coupling is the dominant cause of crosstalk-induced delay in global-level chip interconnects. For our work, a standard three-line bus architecture is used to calculate crosstalk-induced delay for emerging carbon-based chip interconnect materials.

The capacitive coupling ($C_{CCU}$) for Cu [39,40], MLGNR [41], and MWCNT [42] is determined using Equations (17)–(19). Equation (17) is derived using a semi-empirical approach [40]. This model of coupling capacitance considers electric flux variations in the dimensional parameters of the interconnect geometry shown in Figure 7:

$$C_{CCU} = \epsilon_0 \epsilon_r \left[ 1.14 \frac{H}{S} \left( \frac{T}{T + 2.06S} \right)^{0.09} + 0.74 \left( \frac{W}{W + 1.59S} \right)^{1.14} + 1.16 \left( \frac{W}{W + 1.87S} \right)^{0.16} \left( \frac{H}{H + 0.98S} \right)^{1.18} \right]$$

(17)

where $S$, $W$, $H$, and $T$ are the geometrical parameters of the interconnect geometry shown in Figure 7 that are used for crosstalk analysis. The spacing between adjacent interconnect lines is represented by $S$.

For GNR interconnects, the conformal transformation technique formulated in [41] is used to calculate the coupling capacitance. In conformal mapping, the structure is divided into elementary horizontal and vertical line capacitances [41]. Subsequently, these capacitances are summed up to compute overall capacitance. The coupling capacitance
interconnect length is divided into sub-sections of equal-sized and uniform-sized multigate repeaters are inserted at required locations along the interconnect length. For a global length of 1000 μm, seven repeaters are inserted for MWCNT, and doped MLGNRs, while for Cu interconnects 11 repeater stages are required due to higher value of RC parameters. The size of multigate transistors used in repeater as well as driver is considered 100 times the minimum-sized inverter.

The crosstalk-induced delay is determined by applying a step input of 0.8 V at 1 GHz frequency. The load capacitance of 10 aF is used for all calculations in this work. In the case of OP delay calculations, the input signal on the victim line is OP with respect to both aggressor lines. It is worst-case delay, as both aggressor lines simultaneously force the signal variations on the victim line opposite the phase direction that deteriorates the delay. Figure 9 depicts OP victim-line waveforms for Cu, neutral/AsF$_3$ MLGNR, and MWCNT-based materials calculated using three-line bus architecture. The minimum delay is exhibited by AsF$_3$-doped MLGNRs and maximum by Cu. In the case of IP delay calculations, the input signal on victim line is IP with respect to both aggressor lines and it has minimal effect on the delay of victim line.

The results illustrated in Figure 10a show crosstalk-induced delay estimated using three-line bus architecture for different types of interconnect materials at global length of 1000 μm. The obtained crosstalk-induced OP delay for n-MLGNR represents a 45.78% reduction compared with the delay for Cu,
while IP delay for n-MLGNR is only 51.4% of the delay obtained with Cu. The greatest differentials in crosstalk-induced OP and IP delay is observed for AsF₅-doped MLGNR of 84.7% and 75.2%, respectively, compared with Cu. In the case of MWCNT, the reductions obtained in crosstalk-induced OP and IP delay are 65.13% and 24.29% compared with Cu. A significant drop in crosstalk-induced OP and IP delay for AsF₅-doped MLGNR are 60.2% and 67.24%, respectively compared with MWCNTs. Thus, crosstalk-induced delay results explicitly suggest that AsF₅-doped MLGNRs are superior in performance than counterparts MWCNTs and Cu.

The average power consumption for crosstalk-induced delay using three-line bus architecture for different types of interconnects at global length of 1000 µm is shown in Figure 10b. The reduction in average power obtained for crosstalk-induced OP delay calculations for n-MLGNR is 75.74%, while for IP delay it is reduced by 33.3% compared with Cu. The highest reduction in average power of 80.22% and 65.94% is achieved for crosstalk-induced OP and IP delay calculations for AsF₅-doped MLGNR compared with Cu. In the case of MWCNT, the fall obtained in average power results for crosstalk-induced OP and IP delay simulations are 67.3% and 39.4% compared with Cu. A significant reduction in average power consumption of 39.5% and 43.7% is obtained for crosstalk-induced OP and IP delay simulations for AsF₅-doped MLGNR compared with MWCNTs.

In the case of MLGNRs, the coupling capacitance is about 5-fold and 1.18-fold lower than that of Cu and MWCNT materials at an interconnect length of 1000 µm. The lower coupling capacitance and scattering resistance of AsF₅-doped MLGNR carbon nanomaterials provide reduced crosstalk-induced delay and average power dissipation for three-line bus architecture of Figure 8. The lower coupling capacitance in AsF₅-doped MLGNR is due to reduced scattering of electrons in z-direction that is electron hopping. Further, the results obtained using π-type ESC model can be further validated using FDTD model reported in previous studies [15,16,20].

5 TRANSPORT ANALYSIS

The transient analysis of equivalent π-type MTL RLC model of bundled MWCNT and MLGNR has been presented in this work. The propagation delay, average power, and EDP parameters are extracted from HSPICE simulations. The delay results of Cu, neutral MLGNR, AsF₅-doped MLGNR, and MWCNT as interconnect materials with interconnect length varying from 100 to 1000 µm is illustrated in Figure 11. The propagation delay results of neutral MLGNR, AsF₅-doped MLGNR, and MWCNT present reductions of 21.6%, 88.4%, and 10.7%, respectively compared with Cu at global interconnect length of 1000 µm. AsF₅-doped MLGNR has a significant reduction of 87% compared with its counterpart MWCNT at length of 1000 µm.

Figure 12 illustrates comparative EDP results of Cu, neutral MLGNR, AsF₅-doped MLGNR, and MWCNT interconnect materials. Neutral and AsF₅-doped MLGNRs present reductions of 41% and 98.6% in EDP compared with Cu at global interconnect length of 1000 µm. The bundled MWCNTs demonstrate an increase of 74.2% in EDP compared with Cu. AsF₅-doped MLGNRs present the most optimal results, being 98.6% and 99.6% better than Cu and
MWCNT counterparts at a length of 1000 μm. The delay and EDP reductions in AsF$_3$-doped MLGNRs are mainly due to their smaller scattering resistances compared with those of Cu and MWCNTs. In addition, the kinetic inductance of AsF$_3$-doped MLGNRs is about 432-fold smaller than that of MWCNTs. The RF, crosstalk, and EDP results of MWCNTs and MLGNRs indicate their potential as ideal choices for interconnects in next-generation interconnects in the near future that will be used with novel nanoelectronic devices, such as three-terminal [43] and four-terminal [44,45] ballistic rectifiers, self-switching devices [46,47], CNTFETs [48], and GNRFETs.

6 | CONCLUSIONS

This paper illustrates comparative RF, crosstalk, and EDP results of carbon-based futuristic IC nanomaterials for chip interconnect applications. The results presented here unambiguously establish the superiority of carbon-based nanomaterials—that is, MWCNTs and MLGNRs—over existing Cu-based chip interconnects. The results demonstrate that AsF$_3$-doped MLGNRs explicitly outperform Cu and bundled MWCNTs in terms of RF parameters such as skin depth, transfer gain, and 3-dB bandwidth. AsF$_3$-doped MLGNRs also outperform Cu and bundled MWCNTs in terms of the crosstalk parameters OP and IP crosstalk-induced delay. Further, the comparative EDP results of AsF$_3$-doped MLGNRs present the most optimal results, being 98.6% and 99.6% better than their Cu and MWCNT counterparts at a length of 1000 μm. The superior 3-dB bandwidth, delay and EDP results of AsF$_3$-doped MLGNRs can be attributed to their higher conductivity, MFP, and momentum relaxation time parameters. Our study’s results suggest that carbon-based nano-interconnects have a bright future in next-generation interconnects.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ORCID

Arun K. Singh 🌐 https://orcid.org/0000-0003-0853-398X

REFERENCES

1. International Technology Roadmap for Semiconductors (ITRS), (2013) Edition Interconnects’ http://www.itrs.net/2013-itsr.html. Accessed 21 Mar 2019
2. Burke, P.J.: Luttinger liquid theory as a model of the gigahertz electrical properties of carbon nanotubes. IEEE Trans. Nanotechnol. 1(5), 129–144 (2002)
3. Naeemi, A., Meindl, J.D.: Conductance modelling for GNR interconnect. IEEE Electron. Device Lett. 28(5), 428–431 (2007)
4. Naeemi, A., Meindl, J.D.: Design and performance modelling for single-walled carbon nanotubes as local, semiglobal, and global interconnects in gigascale integrated systems. IEEE Trans. Electron Devices. 54(1), 26–37 (2007)
5. Naeemi, A., Meindl, J.D.: Compact physics-based circuit models for graphene nanoribbon interconnects. IEEE Trans. Electron Devices. 56(9), 1822–1833 (2009)
6. Nakada, K., et al.: Edge state in graphene ribbons: nanometre size effect and edge shape dependence. Phys. Rev. B Condens. Matter. 54(24), 17954–17961 (1996)
7. Maffucci, A., Miano, G: Electrical properties of graphene for interconnect applications. Appl. Sci 4, 305–317 (2014)
8. Sarkar, D., et al.: High-frequency behaviour of graphene-based interconnects—Part I: impedance modelling. IEEE Trans. Electron Devices. 58(3), 843–852 (2011)
9. Sarkar, D., et al.: High-frequency behaviour of graphene-based interconnects—Part II: impedance analysis and implications for inductor design. IEEE Trans. Electron Devices. 58(3), 853–859 (2011)
10. Bhattacharya, S., Das, D., Rahman, H.: Stability analysis in top contact and side-contact graphene nanoribbon interconnects. IETE J. Res. 63(4), 588–596 (2017)
11. Majumder, M.K., Kuklarn, N.R., Kaushik, B.K.: Frequency response and bandwidth analysis of multi-layer graphene nanoribbon and multi-walled carbon nanotube interconnects. IET Micro Nano Lett. 9(9), 557–560 (2014)
12. Hamedani, S.G., Moayeri, M.H.: Comparative analysis of the crosstalk effects in multilayer graphene nanoribbon and MWCNT interconnects in sub-10 nm technologies. IEEE Trans. Electromagn. Comput. 62(2), 561–570 (2019)
13. Kaushik, B.K., Sarkar, S.: Crosstalk analysis for a CMOS gate driven inductively and capacitively coupled interconnects. Microwave J. 39(12), 1834–1842 (2008)
14. Kaushik, B.K., et al.: Crosstalk analysis of simultaneously switching interconnects. Int. J. Electron. 96(10), 1095–1114 (2009)
