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Performance Analysis of Dielectric Inserted Vertical MLGNR Interconnects

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Abstract: In this paper, the crosstalk analysis of the normal multiple layer graphene nanoribbon (NMLGNR), dielectric MLGNR (DiMLGNR) and doped MLGNR (DMLGNR) is evaluated. The comparative analysis is performed among the NMLGNR, DMLGNR and DiMLGNR. From this it is observed that DiMLGNR exhibits the lowest crosstalk delay. Further, the crosstalk analysis is performed among the normal vertical GNR (NVGNR), doped (VGNR) and the dielectric VGNR (DiVGNR). It is observed that the DiVGNR shows better performance than NVGNR and VGNR. After that the crosstalk analysis is performed by using the ternary logic system by using the active shielding technique. The comparative analysis is performed among the active shielding copper (ASCu), active shielding dielectric horizontal GNR (ASDiHGNR) and the active shielding DiVGNR (ASDiVGNR). Finally, the comparison is done among the all the dielectric inserted interconnects that is DiMLGNR, DiVGNR and ASDiVGNR.

Keywords: Crosstalk, Delay, Interconnects, Shielding

I. INTRODUCTION

As the technology is scaling down, the interconnect delays are more prevailing than the gate delays in the global interconnects [1]. Now-a-days copper (Cu) is used as the interconnect material. But, in Cu the interconnect resistivity is high due to that the interconnect performance is limited by some of the factors like electromigration, scattering effect, grain boundary effect and the skin effect [2, 3]. To overcome these limitations the other interconnect materials are introduced they are the carbon nanotubes (CNTs) and graphene nanoribbons (GNRs). The CNTs and GNRs have high electrical and thermal properties, current carrying capability and large mean free path [4-6]. Due to sp2 hybridized bonds the GNRs and CNTs can possess the large current densities.

GNRs can be used as an effective material for the transistor and interconnects. GNRs can be formed by pattering graphene, pattering is done by packing the carbon atoms tightly in the 2D honeycomb lattice structure. In the fabrication point of view the GNRs are more preferable than the CNTs because of their planar nature in the structure [7]. Depending on the chirality, the GNRs are divided as semiconductive or metallic nature [8]. For the interconnect applications the metallic nature GNRs are more appropriate.

Depending on layers, GNRs are categorized as the single layer GNR (SLGNR) and multilayer GNR (MLGNR). Due to low density of states the SLGNR has the higher resistance. In MLGNR the overall resistance is reduced because in this the number of layers are more due to that conduction paths increases. Further, based on the electrical contact the MLGNRs are classified as top contact MLGNR (TC-MLGNR) and the side contact MLGNR (SC-MLGNR). In the TC-MLGNR only the top most layer is connected to the contact due to that the resistance is increased. But, in SC-MLGNRs all the layers are coupled with the contact cuts then all layers can participate in the conduction due to that the overall resistance is reduced.

The conductivity of graphite can be improved by intercalation doping by exposure to dopant vapour. The conductivity of GNR has influenced by two parameters such as in-plane and c-axis resistances. To improve the conductance of MLGNRs the interaction doping has been suggested and edge specularity effects for MLGNRs are studied. Intercalation doping is the best method to improve the in-plane and c-axis resistances [8]. In [8], it was reported that the MFP and Fermi level has improved when MLGNRs are doped with Arsenic Pentafluoride (AsF_5) intercalation. In MLGNRs the multiple stacked GNRs layers are limited by the electron hopping. And also MLGNRs convert into graphite due to electron hopping. This is due to carbon-carbon bond length linked with elastic strain ensuing from stacked multiple layers [9]. The MFP and number of layers is reduced by this with that the performance of interconnects also reduces. Subsequently, to achieve better performance the MFP should be increased. The MFP can be increased by inserting dielectric medium between the GNR layers. This can limit the GNR to convert as graphite [10].

Depending on the direction of the GNR it is divided into two types they are horizontal GNR (HGNR) and vertical GNR (VGNR). In the HGNR, only the top most layer is contacted with the contact cuts and in the VGNR all the graphene layers are connected with the contact cuts. As of now, mostly all the experiments are done on the HGNR. But, when dielectric GNR placed in vertical direction it can gives better results. By inserting the dielectric between the graphene layers the crosstalk delay is reduced as mentioned in [11]. As per the literature it is observed that dielectric VGNR (DiVGNR) is more preferred than the dielectric HGNR (DiHGNR).

The number of connections and the chip complexity increases by scaling down the technology nodes. By using the binary logic system only a bit of information is transmitted and the complexity of wires increases. To limit these issues the other logic system is introduced that is ternary logic system [12]. In 1974 by Mouftah and Jordan the ternary logic system was proposed [13]. By using ternary logic system more number of information can be transmitted by that the number of pins and wires are reduced. The complexity of the chip also reduces. The radix of the ternary logic system is three and the value is e=2.718. In the ternary logic system there are three logic levels they are logic 0, 1 and 2 those are equivalent to the three voltage levels 0, $0.5v_{dd}$ and v_{dd}. Related to interconnects the ternary logic system requires low switching power. But there is one disadvantage in the ternary logic system that is it is more vulnerable to noise. The crosstalk effect occurs due to their lower noise margin. The crosstalk effect occurs when one signal is interacted with the adjacent signal. The crosstalk effects are reduced by the shielding techniques.

Shielding techniques is classified into two types they are active shielding and passive shielding technique. In the active shielding the shield lines are placed between the signal lines and they switch in the same direction as the signal lines. In the passive shielding technique the ground and power lines are considered as the shield lines. Here the active shielding is used for reducing the crosstalk effects. Here for the Cu, DiHGNR and DiVGNR the active shielding is used Cu using active shielding (ASCu), DiHGNR using active shielding (ASDiHGNR) and DiVGNR using active shielding (ASDiVGNR). However the comparative analysis of ASCu, ASDiHGNR and ASDiVGNR are not reported in the literature yet.

II. Dielectric Inserted Vertical MLGNR

In the Fig.1 the MLGNR cross sectional view is symbolized. The parameters in the figure are height from the ground plane (h), width (w), and thickness (t). The normal MLGNR (NMLGNR) is represented in the Fig.1 (a) and in that $\delta_1$represents the spacing between the two GNR layers and the value is δ_1=0.34nm. The doped MLGNR (DMLGNR) is represented in the Fig.1 (b) and in this by AsF_5 intercalation the doping is performed. In the doped condition the spacing between the two layers is represented by $\delta_2$and the value of δ_2 =0.585nm. When performing the intercalation doping the layer spacing increases then the MFP also increases and the carrier density also increases due to the charge transfer. The dielectric inserted MLGNR (DiMLGNR) is represented in Fig.1 (c). Here the HfO_2 is used as the dielectric medium. By the dielectric insertion between the graphene layers it can control the electron hopping and the carrier mobility among the graphene layers improves. Subsequently, the surface scattering and the MFP is reduced by that the resistance is reduced in every layer.

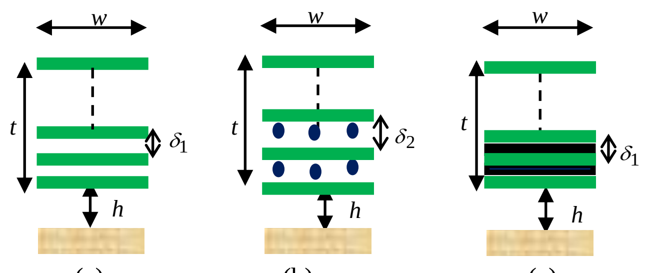

Fig.1. (a) NMLGNR (b) DMLGNR (c) DiMLGNR cross sectional view

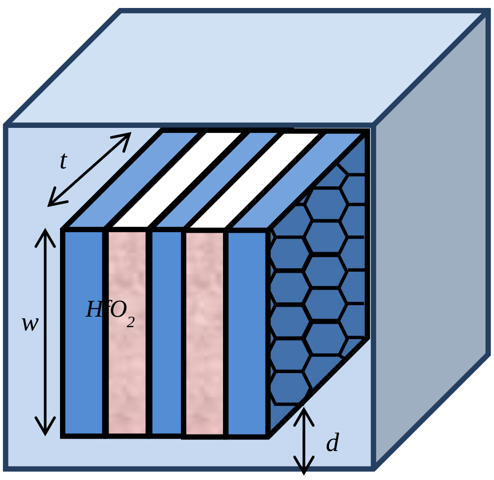

Fig.2 Dielectric inserted VGNR.

The Fig.2 represents the dielectric inserted VGNR. By placing the graphene layers in the vertical direction the resistance is reduced. In the Fig the represented parameters are*t*, *w* and*d* are the thickness, width and the distance from the ground plane respectively. The quantum resistance (R_q) of the MLGNR interconnect can be calculated by the formula

$$R_q = \frac{h/2e^2}{N_{ch} N_L} \quad (1)$$

Here N_L, N_{ch},h and$e$ are the number of layers, number of channels, plank's constant and electronic charge respectively.

The NMLGNR and DiMLGNR interconnect NL can be calculated by

$$N_L = Integer(\frac{t}{\delta_1}) \quad (2)$$

Here $\delta 1$ represents the spacing among the layers in the NMLGNR.

The DMLGNR interconnect NL can be calculated by

$$N_L = Integer(\frac{t}{\delta_1}) \quad (3)$$

Here $\delta 2$ represents the interlayer spacing among the layers in the DMLGNR.

The scattering resistance (R_s) of the DiMLGNR interconnect can be calculated by the formula

$$R_s = \frac{R_q}{\lambda_{mfp}} = \frac{R_q}{\tau v_F} \quad (4)$$

Here $\lambda_{mfp}$is the MFP of electron, is the scattering time and is the fermi velocity of electron. The scattering rate (τ) can be evaluated from [11].

Moreover, the magnetic (L_m) and kinetic (L_k) inductance, the electrostatic (C_e) and quantum (C_q) capacitance can be calculated from [14].

The Fig.3 represents the active shieling technique. In this the shield lines are placed along with the signal lines as shown in Fig.3.

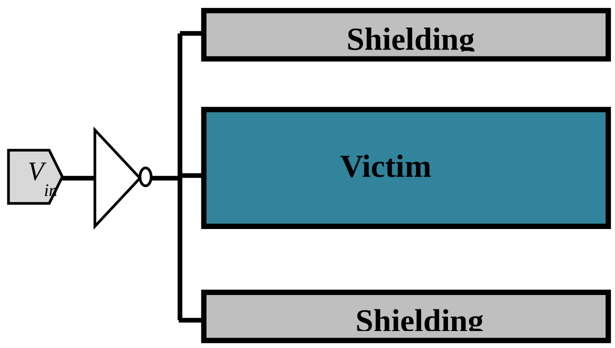

Fig.3. Active shielding technique.

III. Results And Discussion

The crosstalk analysis of normal MLGNR (NMLGNR), doped MLGNR (DMLGNR) and dielectric MLGNR (DiMLGNR) are performed. In Fig.4 and Fig.5 the in-phase and out-phase crosstalk delay of NMLGNR, DMLGNR and DiMLGNR are shown respectively. Here the crosstalk analysis is performed by varying the interconnect length. By varying the interconnect length the crosstalk delay also increases. DiMLGNR has the lowest crosstalk delay than the NMLGNR and DMLGNR.

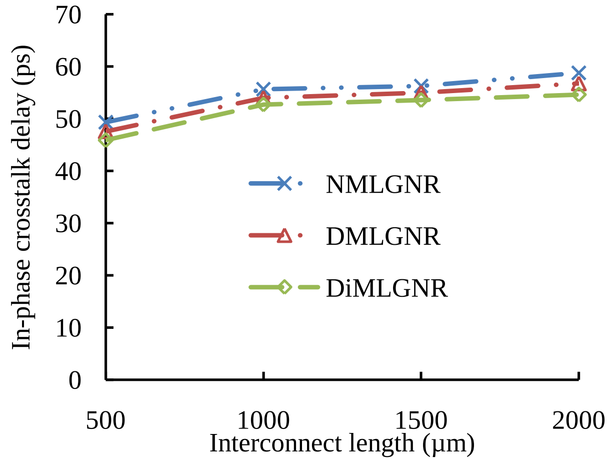

Fig.4. In-phase crosstalk delay of NMLGNR, DMLGNR and DiMLGNR interconnect with varying interconnect length.

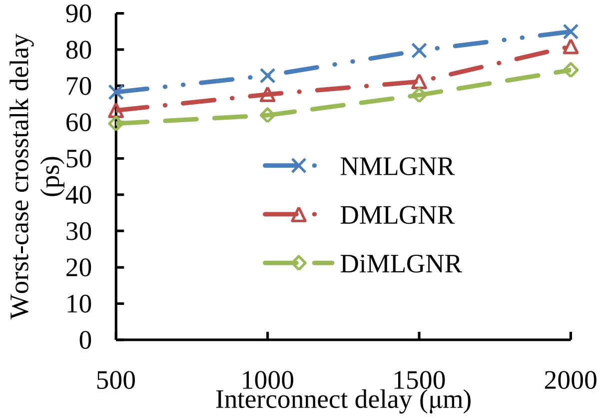

Fig.5. The worst-case crosstalk delay of NMLGNR, DMLGNR and DiMLGNR by varying the interconnect length

In the Fig.6 the power dissipation of the NMLGNR, DMLGNR and DiMLGNR are shown. The lowest power dissipation is for the DiMLGNR interconnect than the NMLGNR and DMLGNR. As the interconnect length increases the power dissipation also increases.

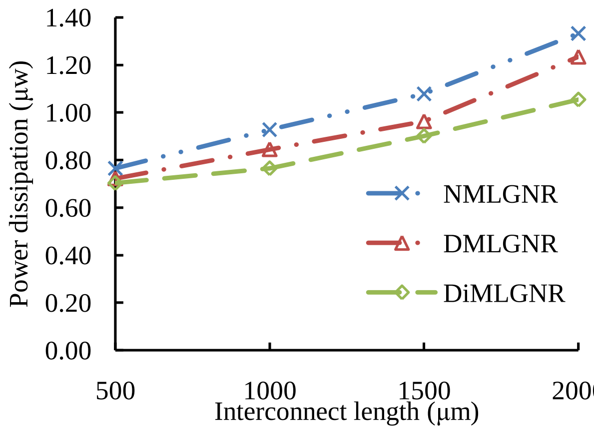

Fig.6. Power dissipation of the NMLGNR,DMLGNR and DiMLGNR interconnect by varying the interconnect length

The crosstalk analysis is performed for the horizontal GNR (HGNR) and the vertical GNR (VGNR). By varying the length of the interconnect from 500-2000µm the crosstalk delay is observed. As theoretically mentioned that VGNR is best than the HGNR. Because in the VGNR there is more conducting paths due to all the layers are connected to the contact cuts. Here the HGNR and VGNR is compared in Fig. 7. In that figure the in-phase and the out-phase of HGNR and VGNR are shown. From that figure it can be observed that VGNR has the lowest delay than the HGNR.

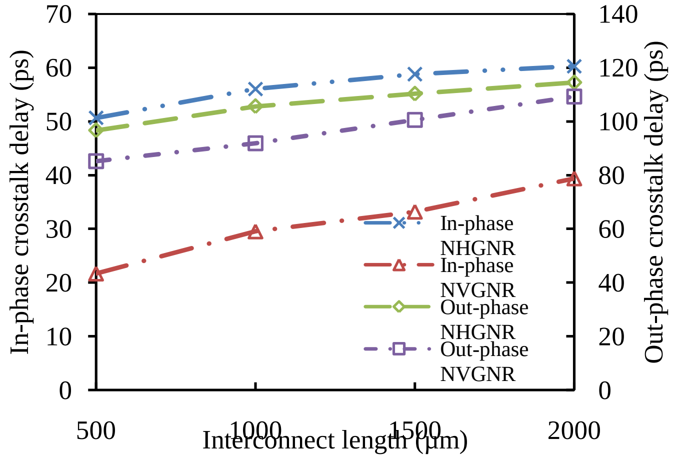

Fig.7. In-phase and out-phase crosstalk delay of HGNR and VGNR

From the above analysis it is proved that the VGNR gives the best results and lowest delay than the HGNR. Now the crosstalk analysis is performed between different types of VGNR's. In Fig.8 and Fig.9 it is shown that the in-phase and out-phase crosstalk analysis for the NVGNR, DVGNR and DiVGNR. The crosstalk is analysed for different interconnect lengths. If the length of the interconnect increases then the crosstalk delay also increases. When compare NVGNR, DVGNR and DiVGNR the lowest crosstalk delay is there for the DiVGNR as shown in Fig.7 and Fig.8

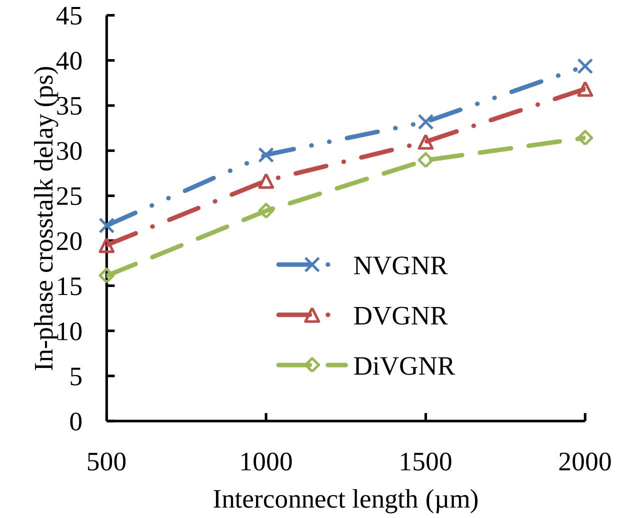

Fig.8 In-phase crosstalk delay of NVGNR, DVGNR, DiVGNR.

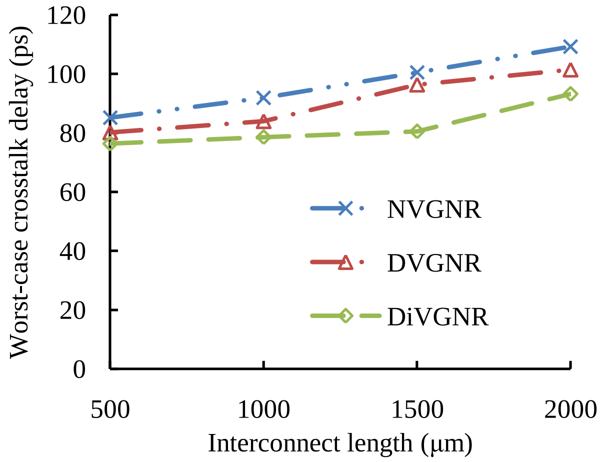

Fig.9 Worst-case crosstalk delay of NVGNR, DVGNR and DiVGNR

The power dissipation of the NVGNR, DVGNR and DiVGNR are shown in Fig.10. The power is more dissipated when the interconnect length increases. The power dissipation is very nominal in all the three cases. There is a more power dissipated in the NVGNR condition. The less power is dissipated in the DiVGNR condition.

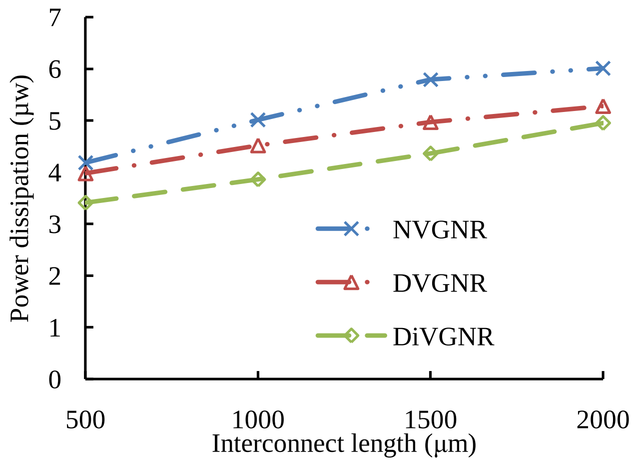

Fig.10 Power dissipation of NVGNR, DVGNR and DiVGNR.

The crosstalk analysis is performed for the three coupled line interconnect system for Cu using active shielding (ASCu), DiHGNR using active shielding (ASDiHGNR), and DiVGNR using active shielding technique (ASDiVGNR). Here the ternary logic system is used instead of the binary logic system and observed the obtained results. In the Fig.11 and Fig.12 the in-phase and out-phase crosstalk delay of the ASCu, ASDiHGNR, ASDiVGNR are shown. Here the crosstalk analysis is performed by varying the length of interconnect. If the interconnect length increases the crosstalk delay also increases. The ASDiVGNR has the lowest crosstalk delay than the ASDiHGNR and ASCu.

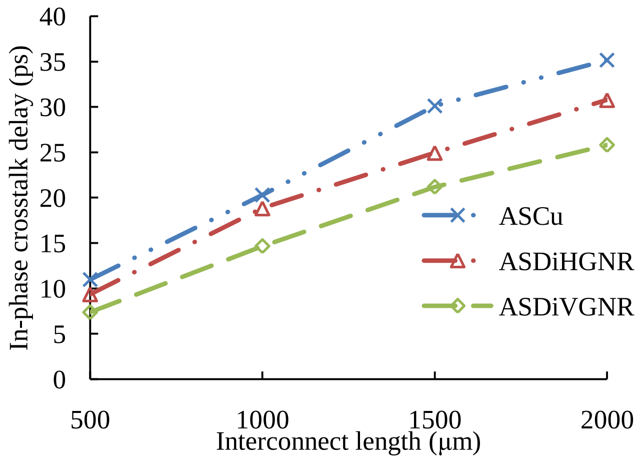

Fig.11 In-phase crosstalk delay of ASCu, ASDiHGNR and ASDiVGNR.

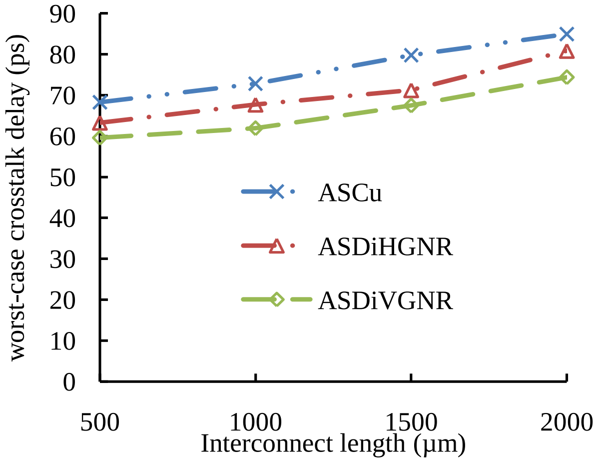

Fig.12. Worst-case crosstalk delay of ASCu, ASDiHGNR and ASDiVGNR.

The power dissipation of the ASCu, ASDiHGNR and ASDiVGNR is shown in Fig.13. There is very small change in the power dissipation of all the three. If the interconnect length increases then the power dissipation also increases. The power dissipation is very low for the ASDiVGNR interconnect than the ASCu and ASDiHGNR interconnects.

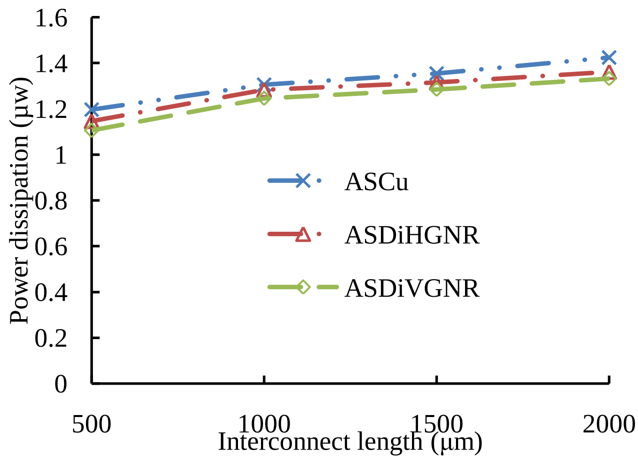

Fig. 13 Power dissipation of the ASCu, ASDiHGNR and ASDiVGNR

Further, the crosstalk analysis is performed among the DiMLGNR, DiVGNR and ASDiVGNR. Because from the above all analysis it can be observed that dielectric inserted interconnects are giving the best results that is the lowest delay is produced. In the Fig.14 and Fig.15 the in-phase and out-phase crosstalk delay of the DiMLGNR, DiVGNR and ASDiVGNR are shown. From this it can be observed that by increasing the interconnect length the crosstalk delay also increases. And, the ASDiVGNR has the lowest crosstalk delay when compared with DiMLGNR and DiVGNR.

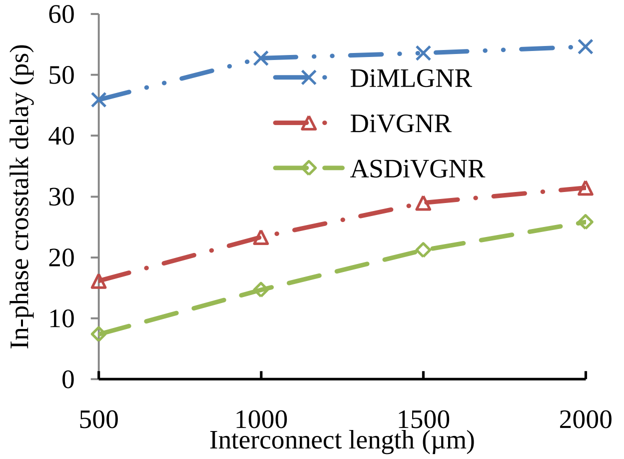

Fig. 14 In-phase crosstalk delay of DiMLGNR, DiVGNR and ASDiVGNR.

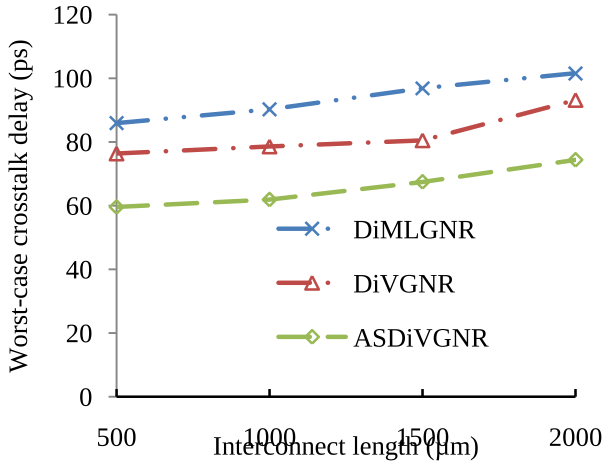

Fig. 15.Worst-case crosstalk delay of DiMLGNR, DiVGNR and ASDiVGNR.

IV. CONCLUSION

The crosstalk analysis of different interconnects are performed in this work by changing the interconnect length. First the crosstalk analysis is performed for the NMLGNR, DMLGNR and DiMLGNR. From this it is observed that the DiMLGNR has the lowest delay than the NMLGNR and DMLGNR. Then after, the crosstalk analysis is performed among HGNR and VGNR. From that it is noticed that VGNR gives the best results. Further, among the different types of VGNR's the crosstalk analysis is performed. Among NVGNR, DVGNR and DiVGNR the crosstalk analysis is performed and noticed that DiVGNR gives the lowest crosstalk delay than the NVGNR and DVGNR. After that the analysis is done by using the ternary logic system and the active shielding technique. For the ASCu, ASDiHGNR and ASDiVGNR the crosstalk analysis is performed. From that the ASDiVGNR has the lowest crosstalk delay than the ASCu and ASDiHGNR. From all those results it is observed that dielectric inserted GNRs are giving the lowest crosstalk delay. So, the comparative analysis is performed among the DiMLGNR, DiVGNR and ASDiVGNR. From that is observed that the ASDiVGNR has the lowest crosstalk delay than the DiMLGNR and DiVGNR.

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