

Impact of Process Variations on Delay in Carbon Nanotube Based Bus Interconnects At Different Technology Nodes



Ch. Praveen Kumar, E. Sreenivasa Rao, P. Chandrasekhar

Abstract: This paper presents the impact of process variations in carbon nanotube based advanced bus interconnects such as single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB). The impact of temperature variations on parasitics of interconnects for variable interconnects at different technology nodes is analyzed. From the analysis, it reveals that the mixed bundle carbon nanotube offering the lower parasitics even higher temperatures compared to SWCNT and MWCNT which leads to lower delay and crosstalk effect when it is used in bus interconnects. Further we have also done delay analysis by changing the bundle area, number of shells and metallic ratio of three interconnect structures with the insertion of obtained parasitics using empirical formulas. It is proven that the mixed CNT (MCB) interconnect structures offered a lesser delay compared to other CNT interconnect structures. All the analysis has been done using MATLAB at 22nm and 32nm technology nodes.

Keywords: Single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB), temperature dependent, parasitics, interconnects.

I. INTRODUCTION

In current nanometer regime, MOS technology especially at below 32nm is suffered due to performance degradation of conventional copper interconnect material for very large scale integration (VLSI). Due to increasing interconnect lengths, Cu/ low-k materials have to face certain issues like electromigration. Electromigration induced hillock and void formation can damage the circuit performance at global level of interconnects [1]. To avoid such type of issues, researchers are like to find some alternative material suitable for global on-chip interconnects. In search of novel interconnect materials, carbon nanotubes (CNTs) can be considered as suitable material for global VLSI interconnects. In general, CNTs are well-known as carbon allotropes [1].

The cylindrical structure is basically used to make it by rolling of graphene sheets. Graphene is consisted by monolayer sheet of graphite having sp^2 carbon atomic bond arrangement of honeycomb lattice structures. Encouragingly, the sp^3 bonding of atoms in diamond is weaker than sp^2 bonding in graphite that makes graphene extremely strong material [2]. Therefore, the atomic structure and physical properties of CNTs are unique because it is capable to carry large amount of current [3] as well as provides high thermal conductivity [4], long ballistic transport length [5], and high mechanical strength [6-8].

Basically, CNTs have unique atomic structure made by rolled up graphene sheets. Depending on the number CNT shells, the interconnect lines can be categorized as single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs). A SWCNT bundle is formed by a number of SWCNTs packed in the bundle. In this research paper, the analysis of propagation delay is carried out for SWCNT and MWCNT having different widths and heights. The bundle height and width is varied at different technology nodes such as 32nm and 22nm followed by ITRS 2016 [9]. At the time of fabrication, the primary concern with different diameter controlling methods is just because of limitations as well as effective parameters [10]. Hence, it is impractical to realize a pure MWCNT bundle having CNTs with similar diameters. Therefore, a realistic bundle having CNTs of different diameters can be preferred to fabricate and model in future global VLSI interconnects [11-17]. Due to the less complexity involved in fabrication, this paper focused on a mixed CNT bundle (MCB), wherein SWCNTs and MWCNTs are randomly distributed [10].

This paper presents the impact of process variations in carbon nanotube based advanced bus interconnects such as single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB). The impact of temperature variations on parasitics of interconnects for variable interconnects at different technology nodes is analyzed. From the analysis, it reveals that the mixed bundle carbon nanotube offering the lower parasitics even higher temperatures compared to SWCNT and MWCNT which leads to lower delay and crosstalk effect when it is used in bus interconnects. Further we have also done delay analysis by changing the bundle area, number of shells and metallic ratio of three interconnect structures with the insertion of obtained parasitics using empirical formulas. It is proven that the mixed CNT (MCB) interconnect structures offered a lesser delay compared to other CNT interconnect structures.

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All the analysis has been done using MATLAB at 22nm and 32nm technology nodes.

The rest of the paper is organized as follows: section 2 deals about equivalent RLC Parameters of SWCNT, MWCNT and MCB Interconnects. The time delay analysis with empirical formulas is discussed in section 3. Finally, section 4 concludes the work.

II. EQUIVALENT RLC PARAMETERS OF SWCNT, MWCNT AND MCB INTERCONNECTS

This section deals the estimation of resistance, inductance and capacitance of single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB) interconnects.

A. Single walled carbon nanotube (SWCNT)

Interconnect line is realized by means of a bundle of N equally spaced SWCNTs, fixed at the Vander Waals distance δ , having the same radius r_{cnt} and in the hypothesis of a perfect hexagonal packed structure[18,19].

$$\text{Lattice constant } \Delta = 2r_{cnt} + \delta \quad (1)$$

$$\text{Bundle radius } r_b = r_{cnt} + \Delta(Ns - 1) \quad (2)$$

$$N = 1 + \sum_i^{Ns} 6(i-1) \quad (3)$$

Number of SWCNTs in the hexagonal structure is

$$Ns = \text{int_part} \left[\frac{\frac{\omega}{2} - r_{CNT}}{\Delta} \right] + 1 \quad (4)$$

Number of conducting Channels

$$n = \begin{cases} 2aTr_{CNT} + b & r_{CNT} > \frac{dT}{2T} \\ \frac{2}{3} & r_{CNT} < \frac{dT}{2T} \end{cases} \quad (5)$$

$$\text{Contact Resistance } R_m = \frac{1}{N} \left(\frac{R_i}{2N} + R_{mc} \right) \quad (6)$$

$$\text{Effective Mean Free Path } \gamma = \frac{2 * 10^3}{\left(\frac{T}{T_0} - 2 \right)} r_{CNT} \quad (7)$$

$$\text{Resistance } R = \frac{R_i}{2nN\gamma} \quad (8)$$

$$\text{Capacitance } C = \left\{ \frac{\cosh^{-1} \left[\left(rb + \frac{d}{rb} \right) \right]}{2\pi\epsilon_0\epsilon_r} + \frac{1}{2ntotC_q} \right\}^{-1} \quad (9)$$

$$\text{Inductance } L = \frac{L_K}{2ntot} + L_m \quad (10)$$

B. Multi walled carbon nanotube (MWCNT)

Interconnect line is realized by means of a single MWCNT with an external radius $r_N = W/2$

Number of shells as

$$N = \text{int_part} \left[\frac{rN - r1}{\delta} \right] + 1 \quad (11)$$

The lumped parameter R_m

$$R_m = \left[\sum_{j=1}^N \left(\frac{R_i}{2nj} + R_m \right)^{-1} \right]^{-1} \quad (12)$$

Number of channels

$$n_j = \begin{cases} 2aTr_j + b & r_j > \frac{dT}{2T} \\ \frac{2}{3} & r_j < \frac{dT}{2T} \end{cases} \quad (13)$$

Total Number of conducting Channels n_{tot}

$$n_{tot} = \sum_{j=1}^N n_j \quad (14)$$

$$\text{Mean free path } \gamma = \frac{2 * 10^3}{\left(\frac{T}{T_0} - 2 \right)} r_{CNT} \quad (15)$$

Resistance of Multiwall Carbon Nano Tube

$$R = \sum_{i=1}^{2n_j} (\gamma)^{-1} \quad (16)$$

Capacitance of MWCNT

$$C = \left\{ \frac{\cosh^{-1} \left[\frac{(rN + d)}{r_N} \right]}{2\pi\epsilon_0\epsilon_r} + \frac{1}{C_q} \right\}^{-1} \quad (17)$$

$$\text{Magnetic Inductance } L_K = \frac{h}{v_f * 2 * e^2} \quad (18)$$

Inductance of Multiwall Carbon Nano Tube

$$L = \frac{\mu_0}{2\pi} \cosh^{-1} \left(\frac{(rN + d)}{rN} + \frac{L_K}{2ntot} \right) \quad (19)$$

C. Mixed Carbon Nano Tube (MCB)

A SWCNT and MWCNT bundle of width, W, and height, H, are placed above the ground plane at a distance. The diameter of SWCNT is D, whereas the MWCNT consists of inner shell and outer shell diameters of D_{inner} and D_{outer} , respectively.

The inter shell spacing of MWCNT is equivalent to the Vander-Waal's gap $\delta=0.34\text{nm}$ [18].

The outer shell diameter of MWCNT

$$D_{outer} = D_{inner} + 2 * \delta * (p - 1) \quad (20)$$

Total Number of CNTs in a bundle

$$N_{bundle} = \left[N_a * N_b - \left(\frac{N_a}{2} \right) \right] \quad (21)$$

Number of CNTs in vertical direction

$$N_a = \left[\frac{H}{(D + \delta)} \right] \quad (22)$$

Number of CNTs in Horizontal direction

$$N_a = \left[\frac{w}{(D + \delta)} \right] \quad (23)$$

Conducting Channels of each shell

$$N_i(D_i) = n_j = \left\{ \begin{array}{ll} K_1 T D_i + K_2 & D_i > \frac{dT}{2T} \\ \frac{2}{3} & D_i < \frac{dT}{2T} \end{array} \right\} \quad (24)$$

Total Number of Conducting Channels of bundle SWCNT

$$(N_{tot})_{SWCNT} = (N_{bundle})_{SWCNT} * N_i(D_i) \quad (25)$$

Total Number of Conducting Channels of bundle MWCNT

$$(N_{tot})_{MWCNT} = (N_{bundle})_{MWCNT} * \sum_{i=0}^p N_i(D_i) \quad (26)$$

Quantum resistance

$$R_q = \left[\left(\frac{h}{2 * e^2 * ((N_{tot})_{SWCNT})} \right)^{-1} + \left(\frac{h}{2 * e^2 * ((N_{tot})_{MWCNT})} \right)^{-1} \right]^{-1} \quad (27)$$

Scattering Resistance

$$R_s = \left[\left(\frac{h}{2 * e^2 * \gamma * ((N_{tot})_{SWCNT})} \right)^{-1} + \left(\frac{h}{2 * e^2 * \gamma * ((N_{tot})_{MWCNT})} \right)^{-1} \right]^{-1} \quad (28)$$

Kinetic Inductance

$$L_K = \left[\left(\frac{L_{K0}}{(N_{tot})_{SWCNT}} \right)^{-1} + \left(\frac{L_{K0}}{(N_{tot})_{MWCNT}} \right)^{-1} \right]^{-1} \quad (29)$$

Magnetic Inductance

$$L_M = \frac{\mu_0}{2\pi} \cosh^{-1} \left(\frac{(D_{outer} + 2Ht)}{D_{outer}} \right) \quad (30)$$

Quantum Capacitance

$$C_q = \frac{2 * e^2}{h * v_f} * \left[(N_{tot})_{SWCNT} + (N_{tot})_{MWCNT} \right] \quad (31)$$

Electrostatic Capacitance

$$C_e = \frac{2 * \pi * \epsilon_0 * \epsilon_r}{\cosh^{-1} \left(\frac{(D_{outer} + 2Ht)}{D_{outer}} \right)} \quad (32)$$

D. RLC Values of SWCNT, MWCNT and MCB at different technology nodes

In this section, we have calculated the resistance, capacitance and inductance values of different interconnect structures such as SWCNT, MWCNT and MCB by varying length at 22nm and 32nm technology nodes. From the analysis, it is evident that the resistance, inductance and capacitance is very less in mixed CNTs compared to the MWCNT and SWCNT interconnects. The resistance, capacitance and inductance of three interconnect structures such as MCB, MWCNT and SWCNT are tabulated in table I by varying the interconnect length at 22nm. For all the MATLAB simulations MCB has given a very less R, L, C values. We have also tabulated the resistance, capacitance and inductance of for the same three interconnect structures such as MCB, MWCNT and SWCNT in table II by varying the interconnect length at 32nm. All the values calculated at room temperature and even temperature changes, the RLC parameters changes. These RLC values are used to analyze time delay performance of different interconnects by changing the temperature at different technology nodes.

III. TIME DELAY ANALYSIS

This section deals the time delay analysis of single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB) interconnects. To evaluate the performance of carbon nano interconnects, the time delay analysis has to perform. The analytical expression has considered for examine the 50% time delay is [19]

$$T_{50\%} = \left(1.48 * q + e^{-2.9 * q^{1.35}} \right) * \sqrt{L_l (C_l + C_L)} \quad (33)$$

$$q = \frac{2(R_T + R_m)(C_l + C_L) + R_l(C_l + 2C_l)}{\sqrt[4]{L_l(C_l + C_L)}} \quad (34)$$

Where R_T and C_L represent the input resistance and load capacitance.

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Table I: Estimated R, L and C Values of MCB, MWCNT and SWCNT at 22nm

Length (μm)	MCB			MWCNT			SWCNT		
	R (KΩ)	L (nH)	C (fF)	R (KΩ)	L (nH)	C (fF)	R (KΩ)	L (nH)	C (fF)
200	1.38	3.22	1.964	2.08	52.6	16.1	45	56.2	11.9
500	3.4	8.05	4.91	5.2	131	40.4	112.5	140	29.8
1000	6.9	16.1	9.82	10.4	263	80.9	225	281	59.7
1500	10.3	24.2	14.7	15.6	394	121	337	421	89
2000	13.8	32.3	19.6	20.8	526	161	450	562	119

Table II: Estimated R, L and C Values of MCB, MWCNT and SWCNT at 32nm

Length (μm)	MCB			MWCNT			SWCNT		
	R (KΩ)	L (nH)	C (fF)	R (KΩ)	L (nH)	C (fF)	R (KΩ)	L (nH)	C (fF)
200	0.6	1.54	1.97	1.2	32	16.6	28.8	36	11.99
500	1.6	3.85	4.93	3.02	80	41.6	72	90.3	30.11
1000	3.2	7.7	9.93	6.04	160	83	144	180	60.7
1500	4.8	11.5	14.81	9.06	240	124	216	270	89.6
2000	6.94	15.4	19.65	12.08	320	166	288	361	119.8

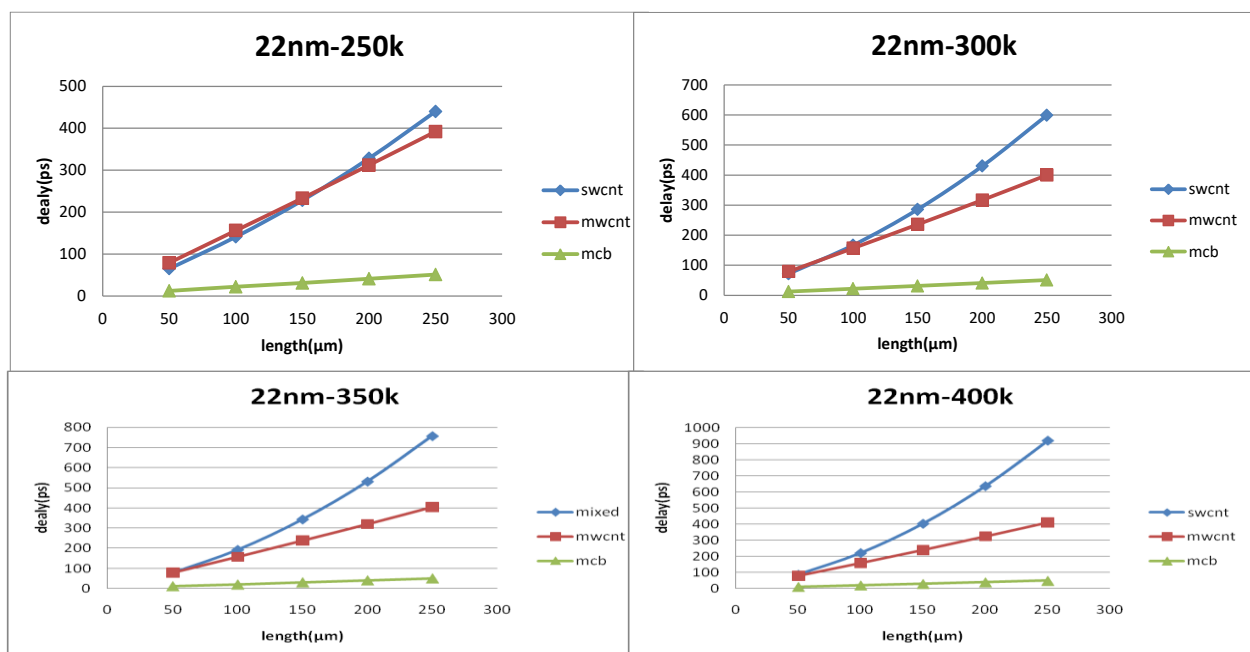


Figure 1: Delay variation of SWCNT, MWCNT and MCB interconnects for different temperatures by varying the length at 22nm technology

From the time delay expressions, we have estimated the time delay for different interconnect structures such as MCB, SWCNT and MWCNT by varying the process parameters such as temperature, bundle area and metallic ratio with respect to length of the interconnect. All the

interconnect dimensions are considered from ITRS data at different technology nodes such as 22nm and 32nm [9].

The time delay analyzed and plotted in figure1 and figure 2 for different temperatures such as 250k, 300k, 350k, 400k with respect to interconnect length variation. In all the graphs mixed CNT bundle interconnect has given a better performance compared to other interconnects such as SWCNT and MWCNT. Actual process parameters variation range is for temperature is 293.4k to 393.5k, for metallic ratio is considered 1/3, but it can vary maximum 30% and for densely packed bundle area is considered $0.077\mu\text{m}^2$, it can also vary maximum 10% in width and height [18]. We

have also estimated the delay values at room temperature (300k), 10% bundle area variation, metallic ratio 0.3 (30% variation) for all interconnect structures such as SWCNT, 3-shell MWCNT, 5-shell MWCNT and MCB at 22nm and 32nm technology nodes, shown in figure 3, figure 4 and figure 5. All the simulations has done in MATLAB and it is evident that the mixed CNT (MCB) interconnect structure offered a lesser delay compared to other CNT interconnect structures.

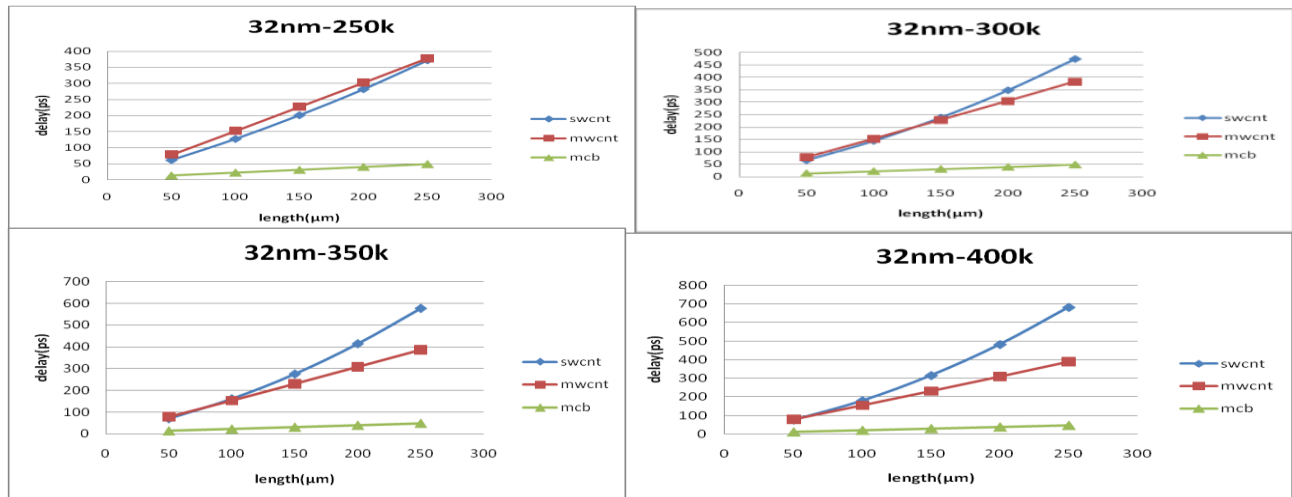


Figure 2: Delay variation of SWCNT, MWCNT and MCB interconnects for different temperatures by varying the length at 32nm technology

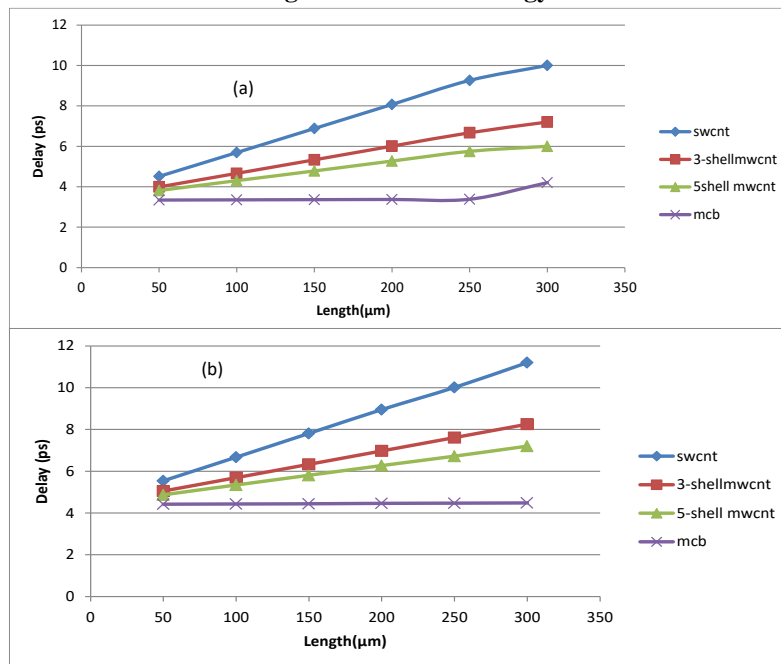


Figure 3: Delay variation of SWCNT, MWCNT (3 and 5-shell) and MCB interconnects for 300k temperature by varying the length at (a) 22nm technology (b) 32nm technology

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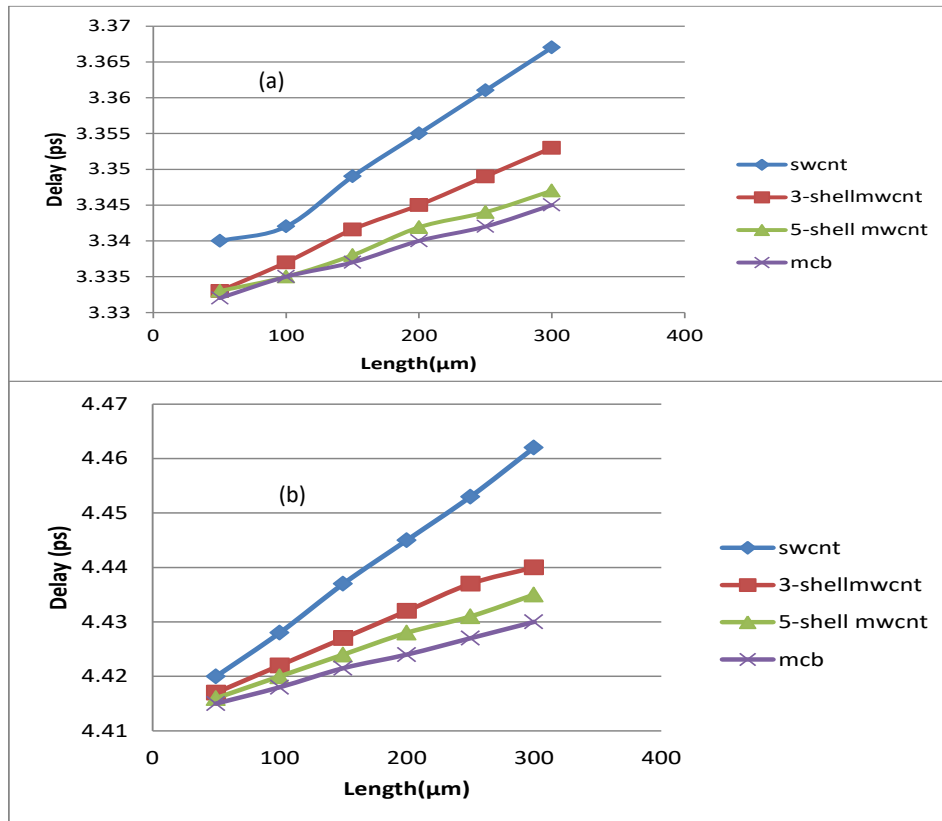


Figure 4: Delay variation of SWCNT, MWCNT (3 and 5-shell) and MCB interconnects for 10% variation of bundle area by varying the length at (a) 22nm technology (b) 32nm technology

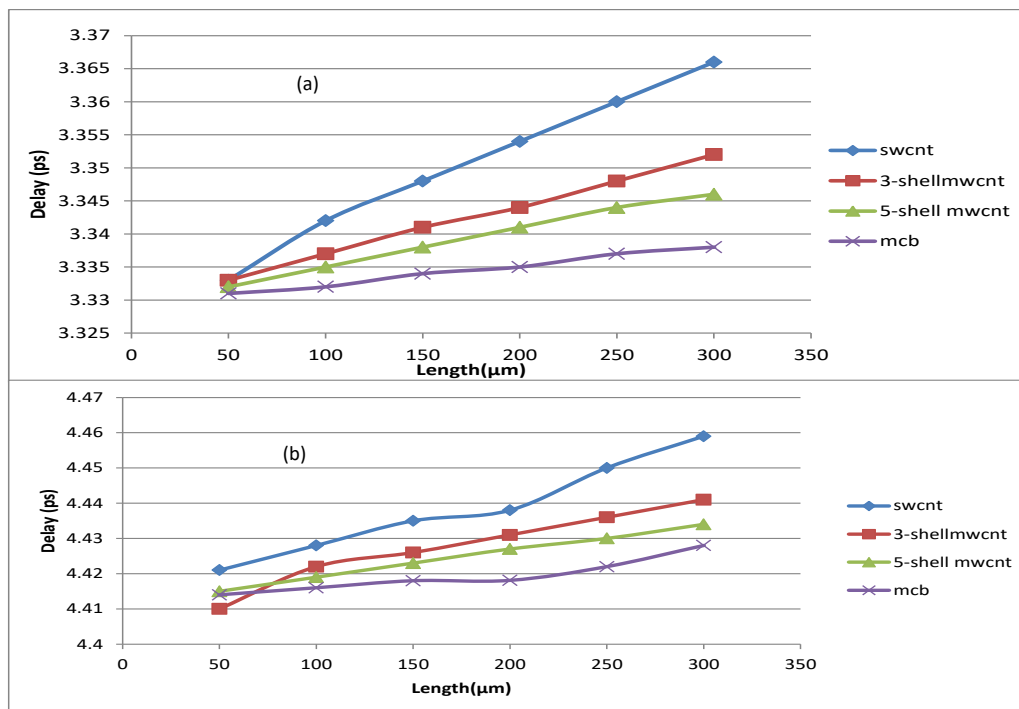


Figure 5: Delay variation of SWCNT, MWCNT (3 and 5-shell) and MCB interconnects for 30% variation of metallic ratio by varying the length at (a) 22nm technology (b) 32nm technology

IV. CONCLUSION

The impact of process variations in carbon nanotube based advanced bus interconnects such as single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and mixed carbon nanotube bundle (MCB) are analyzed and the tabular and graphical observations are

reported. From the analysis, it reveal that the mixed bundle carbon nanotube offering the lower paracitics even higher temperatures compared to SWCNT and MWCNT which leads to offer lower delay and crosstalk. In addition,

also analyzed the delay by changing the bundle area, number of shells and metallic ratio of three interconnect structures with the insertion of obtained parasitics parameters at 22nm and 32nm technology nodes. It is proven that the mixed CNT (MCB) interconnect structures offered a lesser delay compared to other CNT interconnect structures.

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