

**“STUDY THE TEMPERATURE-DEPENDENT
MODELING AND PERFORMANCE ANALYSIS OF
MIXED CARBON NANOTUBE (CNT) BUNDLE BASED
VLSI INTERCONNECTS”**

Thesis Submitted towards the partial fulfillment for the

Degree of

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VLSI Design

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CERTIFICATE

I hereby declare that the work which is being presented in the thesis entitled "**Study the Temperature-Dependent Modeling and Performance Analysis of Mixed Carbon Nanotube (CNT) Bundle based VLSI Interconnects**" in partial fulfillment of the requirement for the award of degree of M.Tech. (VLSI Design) at Electronics and Communication Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Mayank Kumar Rai**, Assistant Professor, ECED.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of my degree.

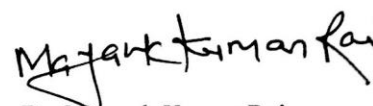
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(Harsh Garg)

Abstract

The resistance of copper (Cu) interconnect is increasing with advancement of technology nodes in deep submicron (DSM) which causes degradation in interconnect performances in terms of crosstalk and propagation delay. Recent research shows that the carbon nanotubes (CNT) are preferred over Cu interconnects due to their high current carrying capacity and high thermal conductivity. CNT has high equivalent resistance but it reduces to very small value when it is used in bundle. However, a realistic CNT bundle contains a mix of Single walled carbon nanotubes (SWCNTs) and Multi walled carbon nanotubes (MWCNTs). So, many researchers proposed different structures of mixed CNT bundle (MCB) based on the different arrangements of SWCNT and MWCNT. Currently primary focus of researchers is on the performance analysis of different structures of MCB.

Beyond 45nm technology node, due to temperature variation there is significant change in the performance of the CNT based interconnects. So temperature-dependent performance analysis of interconnects is very important. A lot of research has been done for the temperature-dependent analysis of SWCNT and MWCNT individually. However no analysis has been made to analyze temperature-dependent performance analysis for coupled mixed CNT bundle based interconnects.

In this thesis, the temperature-dependent circuit modeling and performance analysis in terms of crosstalk in capacitively coupled MCB interconnects, at the far end of victim line, have been analyzed with four different structures of mixed CNT bundles (MCB-1, MCB-2, MCB-3 and MCB-4) constituted under case-1 and case-2 at 22 nm technology node. The impact of tunneling and intershell coupling between neighbouring shells on temperature-dependent equivalent circuit parameters of an MWCNT bundle are also critically analyzed and employed for different structures of MCBs under case-1. A similar analysis is performed for Cu interconnects and comparisons are made between results obtained through these analyses over a temperature ranging from 300K to 500K.

The SPICE simulation results reveal that, compared with all structures of MCBs under case-1 and case-2, with rise in temperature from 300K to 500K, crosstalk -induced noise voltage levels at the far end of victim line, are found to be significantly large in Cu. It is also observed that due to the dominance of larger temperature-dependent resistance and ground capacitance in case-1, the MCB-2 is of lower crosstalk-induced noise voltage levels than other structures of MCBs. On the other hand, the MCB-1 has smaller time duration of victim output. Results further reveal that, compared with case-2 of MCB, with rise in temperatures, the victim line gets less prone to crosstalk-induced noise in MCB interconnects constituted under case-1, due to tunneling effects and intershell coupling between neighbouring shells. Based on these comparative results, a promising structure of mixed CNT bundle (MCB-2) has been proposed among other structures under the consideration of tunneling effects and intershell coupling (case-1).

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List of Acronyms

CMOS	Complementary Metal Oxide Semiconductor
CNT	Carbon Nanotube
EDP	Energy Delay Product
ESC	Equivalent Single Conductor
GHz	Giga Hertz
IC	Integrated Circuit
ITRS	International Technology Roadmap for Semiconductor
MFP	Mean Free Path
MWCNT	Multi Walled Carbon Nanotube
PDP	Power Delay Product
RLC	Resistance-Inductance-Capacitance
SPICE	Simulation Program with Integrated Circuit Emphasis
SWCNT	Single Walled Carbon Nanotube
VLSI	Very Large Scale Integration
MCB	Mixed CNT Bundle

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List of Symbols

A	Area of cross-section
K_b	Boltzmann's constant
R_c	Contact resistance
C_c	Coupling capacitance
ϵ	Dielectric constant
D	Distance between ground and interconnect
λ_{eff}	Effective mean free path of CNT
C_e	Electrostatic capacitance
E_f	Fermi Energy
v_f	Fermi velocity of electrons
C_g	Ground capacitance
L_k	Kinetic inductance
L	Length of interconnect
L_m	Magnetic inductance
N_{ch}	Number of conducting channels
N	Number of shells
μ_0	Permeability
H	Planck's constant
C_q	Quantum capacitance
R_q	Quantum resistance
R_o	Resistance of copper at 300K
R_s	Scattering resistance
S	Separation between adjacent interconnects
W	Width of interconnect
T	Thickness of interconnects

Chapter 1

Introduction and Statement of the Problems

A VLSI interconnect is made up of conducting material that provides electrical connection between two or more nodes of the integrated circuit formed on the Silicon chip. Interconnects are multi-conductor lines that exist on different physical planes. Interconnect in VLSI integrated circuits can be modeled as a lossy transmission line in very high speed integrated circuits [1].



Fig. 1.1. VLSI Interconnect [2].

A VLSI interconnect plays an important role in deep submicron technology as interconnect can't be assumed as simple resistor in this technology. In deep sub micron technology associated parasitic such as inductance and capacitance comes into the picture so they have to be considered. Delay and crosstalk noise introduces in propagating signal due to these parasitic through interconnects.

1.1 Types of Interconnects

Interconnects can be classified of three types based on dimensions which are given below:

- Local : used for very short interconnects at the device level.
- Intermediate/Semi global: used to connect devices within a block.
- Global : used to connect long interconnects between the blocks, including power, ground and clocks.

Interconnect can be local, intermediate or global as per requirement. Local interconnects are the first level or lowest/basic level interconnect. These interconnects are generally used in connecting gate, drain, source in MOS technology and bases, collector, emitter in bipolar technology. Local interconnects can be made of high resistive materials in comparison to global interconnects as they are of small length. But they also should withstand with high temperatures. Global interconnects made up of generally Aluminium/Copper material. Generally, these interconnect travel over long distance between different parts and different devices of the integrated circuit so it should be made of low resistive material. As the complexity has been increased in modern integrated circuit technology so the intermediate interconnect is introduced in between local and global interconnect [3].

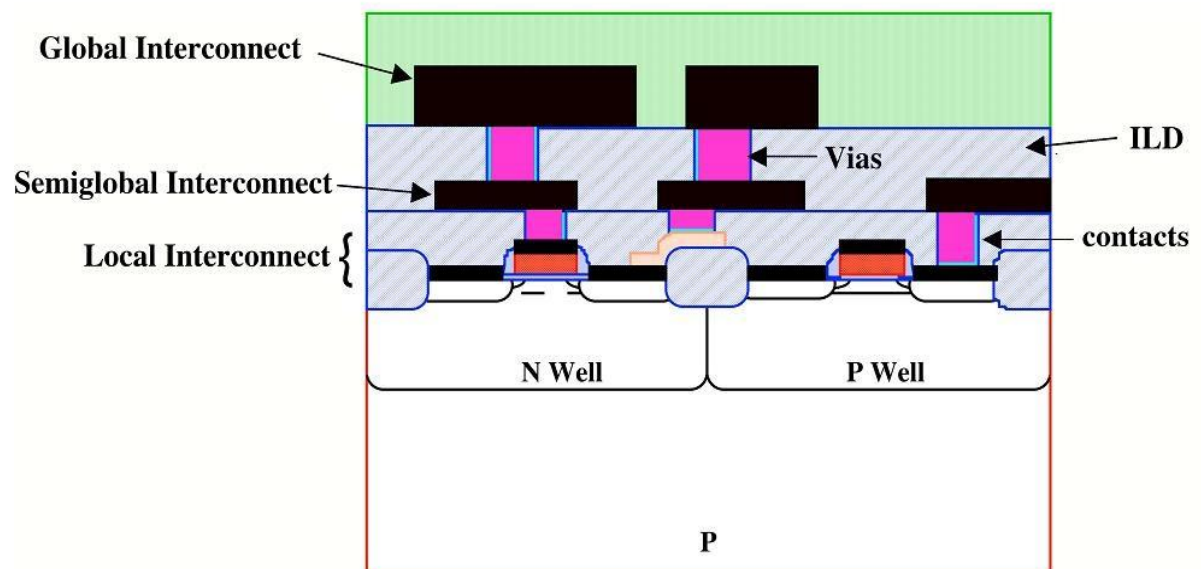


Fig. 1.2. Types of Interconnect [3].

Interconnects are separated from each other and from active areas using dielectric material. These layers separating interconnects from each other are called intermetal dielectrics or IMD. The layer which separates interconnects are given different names: first level dielectric, pre-metal dielectric, dielectric -1 etc. Generally term a use for this is

first level dielectric. Metallization structures are getting more attention as circuit elements decrease in size and circuit areas increase in size [3].

1.2 Scaling of Interconnect Line and Devices

The improvements of technology nodes are causing increase in both device density and interconnect density. The area of MOS transistor can be scaled down by reducing width and length of the channel of transistor. Based on constant field scaling, different scaling factors for all the parameters are given in Table 1.1 [4].

Table 1.1. Scaling of Interconnect.

Device/Circuit Parameter	Scaling Factor
Dimensions (W, L, H)	$1/S$
Voltage	$1/S$
Field	1
Line Resistance	S
Line Capacitance	$1/S$
Gate Delay	1

In case of constant field scaling, scaling factor of voltage and length is $1/S$ so scaling factor of constant field is 1. For line resistance scaling factor is S, as the scaling factor for the length is $1/S$ and for area is $1/S^2$. Scaling of dimension for local and global interconnects is shown in Fig.1.3. It can be seen that more than one chip can be placed after scaling in the area before scaling of the chip. So, device density increases multiple time with the scaling depends on the scaling factor.

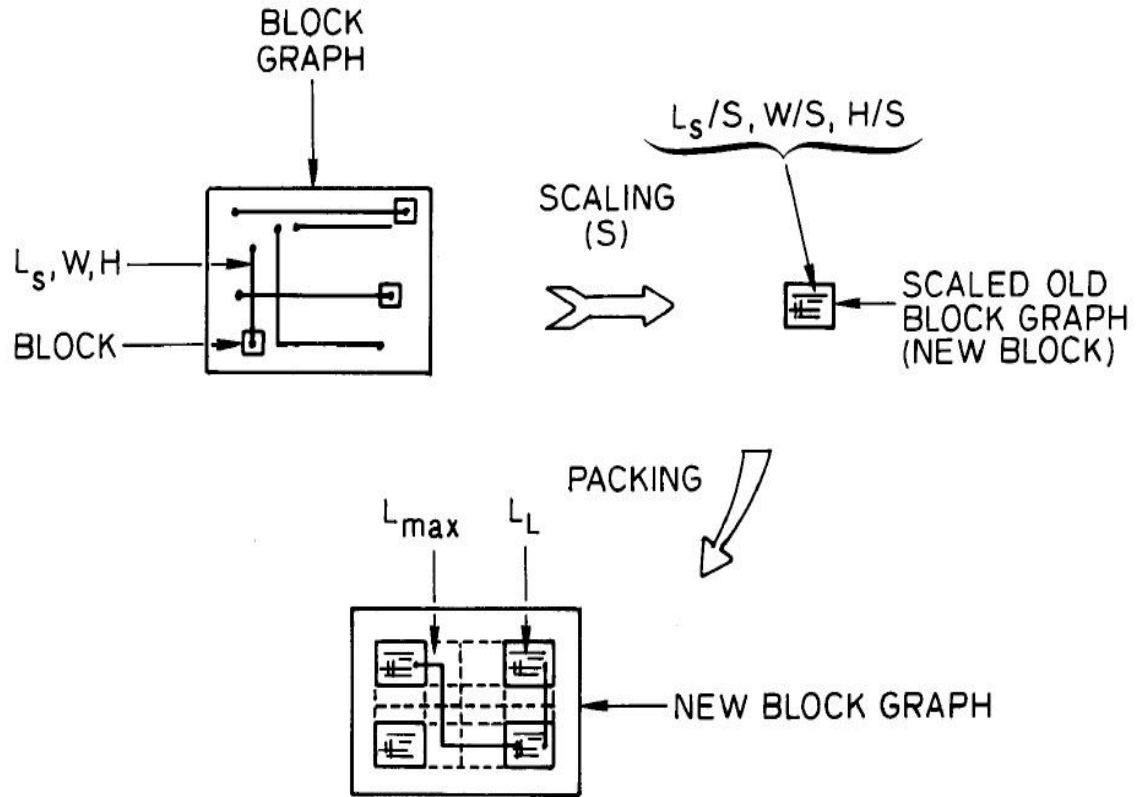


Fig. 1.3. Scaling of a chip and interconnections [3].

1.3 Previously Used Interconnects:

Earlier time Aluminium was used commonly as interconnect material. It was because of its good conductivity. Also Aluminium forms good ohmic contact with Silicon. As the feature size is reducing continuously, length of the on chip interconnect is increasing. Resistance, inductance and capacitance will increase with the increase in length of interconnect [4]. This further results in an increase in interconnects signal propagation delay. As the technology is scaling, current density of interconnect increases. With the high current density, a problem comes in the Aluminium interconnect i.e. electro migration takes place. Later Copper was preferred over the Aluminium due to its capability of withstand 5 times more current density compared with Aluminium, high conductivity [5] and high melting point. High melting point provides better thermal stability to Copper. Because of all above facts copper is most preferable interconnect material till present day.

1.4 Problems with existing Interconnect material:

Due to scaling of the technology, some problems are facing by industry in the interconnect materials, which are described below:

- **Grain boundary effect:** It is the interface between two grains or crystallites, in a polycrystalline material. Grain boundaries are the fabrication defects in the crystal structure, and due to which electrical and thermal stability decreases. In copper this effect is more as compared with conventional polycrystalline material [6].

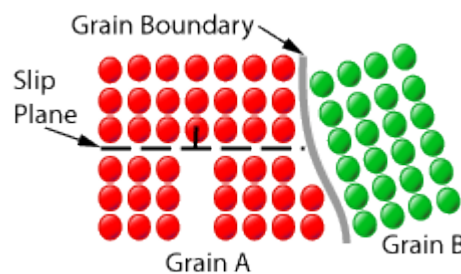


Fig. 1.4. Grain boundary effect [7].

- **Electro-migration:** As the momentum transfers between diffusing metal atoms and conducting electrons, the gradual movement of the ions in a conductor is called electro-migration. Due to which there can be eventual loss of connections. The electro migration resistivity of copper is although high. As scaling of VLSI circuits continues, interconnects are subject to increasingly high current densities [6].

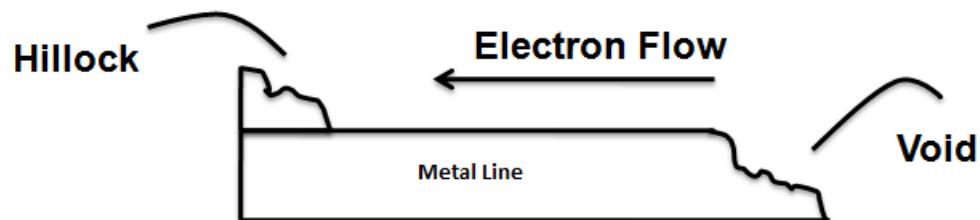


Fig. 1.5. Electro-migration leads to void [8].

- **Surface Scattering:** Mean free path is the average distance that an electron can travels between successive impacts. As the technology scaling occurs, mean free

path of the charge carriers is decreasing, which can be observed by increased surface scattering due to line narrowing. Both the grain boundaries and the surface of the solids are the barriers for the charge carriers.

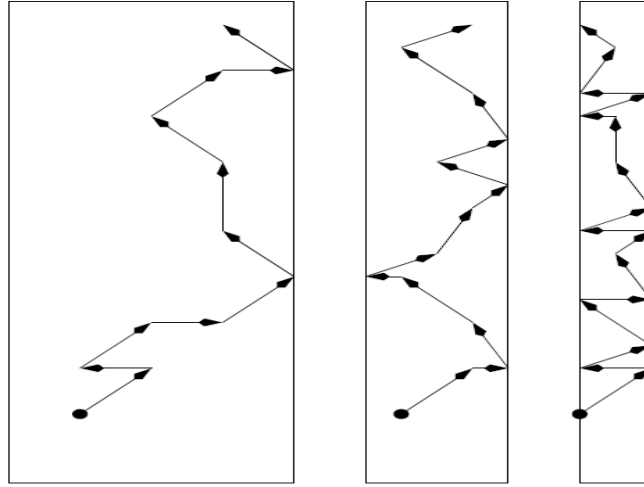


Fig. 1.6. Increased surface scattering from line narrowing of interconnect [9].

1.5 Classification of CNT based interconnect:

Until the mid 1980's, it was thought that only two physical forms of pure solid carbon i.e. diamond and graphite exists. Both have different physical structures as well as properties but their atoms are covalently bonded with each other. So, both above discussed forms of carbon atoms are called allotropes. In 1985, some researchers led by Richard Smalley and Robert Curl of Rice University in Houston made an interesting discovery i.e. C_{60} . This new allotrope of carbon with unique properties did not end with spherical molecules, also discovered that carbon atoms can also be in cylindrical shape. Initially these tubes were named as “buckytubes” but now are known as **Carbon Nanotubes**.

Carbon Nanotubes, long, thin cylinders of carbon, were discovered in 1991 by Sumio Iijima. They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder. According to Moore's Law, by 2019 transistor will just few atoms in width. CNT, have thickness approx. equal to 1 atom, with diameters of only 1 to 2 nm, so may be the perfect solution for the moore curve. We possibly cannot go beyond that. So CNT can be the future VLSI interconnect [10].

1.5.1 Classification of Carbon Nanotubes:

- **Based on Geometry:**
 - i. **Metallic**
 - ii. **Semiconducting**

Semiconducting or metallic characteristics of nanotube depends on geometric arrangement of their carbon atoms. Statistically, it is analyzed that a natural mix of CNTs will have the proportion of metallic and semiconducting chirality is 1/2 [11]. A small increase in diameter has a major impact on the conduction properties of carbon nanotubes. CNTs can have distinctive chiralities relying upon the course they are rolled up, which suggests that the CNTs are metallic or semiconducting [12].

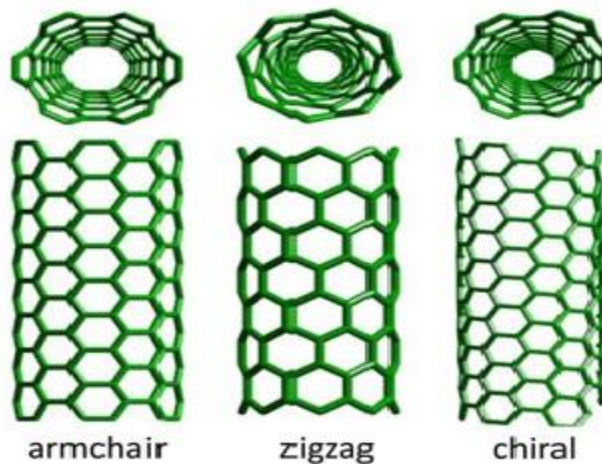


Fig. 1.7. Various Forms of CNTs [14].

Note that all tubes having arm- chair chirality are metallic, as well as tubes with indices $(m-n=3)$. The (n,m) indices tells the electronic structure of nanotube. CNTs for which $n-m=3q$ are metallic, and those for which $n-m$ is not $3q$ are semiconducting. Here, q is an integer. Armchair CNT is metallic as there is no any Band gap between conduction and valance band but in the case of zig zag a tiny band gap is there that make it semiconducting in nature. Semi conductive nanotubes can be used for the channel of carbon nanotube field-effect transistors (CNFET). Conductive (or metallic) nanotubes use for today's very deep submicron (silicon-based) electronics [13].

- **Based on Layers:**
 - i. **SWCNT**
 - ii. **MWCNT**

SWCNT stands for Single walled carbon nanotube, as name suggests consists of one thin wall of graphene sheet whereas MWCNT (Multi walled Carbon nanotube) consists of multiples of concentric SWCNTs. Due to high thermal and mechanical stability, metallic CNTs are attractive. Also metallic CNT have the capability of carry high current density. Generally MWCNTs are metallic. Chirality can be defined as the direction in which they get rolled up. MWCNT can be easily fabricated in comparison to SWCNT as growth process is easy to control. SWCNT can be zigzag (for semiconducting) or arm chair (for metallic).

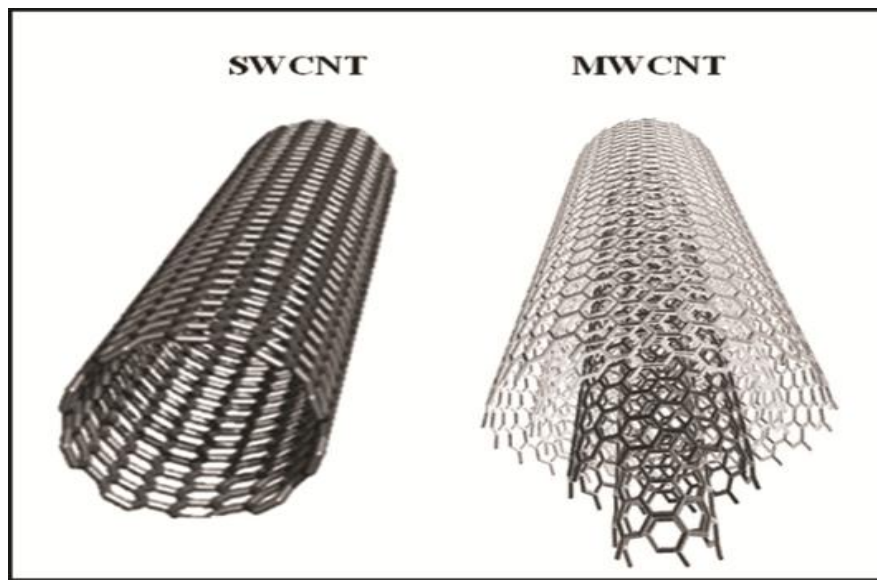


Fig. 1.8. Various types of CNTs based on layers [14].

1.6 CNT in Bundle:

Individual CNT either SWCNT or MWCNT resistance is very high. So, CNTs are combined parallel to form a bundle to reduce the overall resistance. In bundle, coupling between the interconnects cannot be ignored. Bundles can be of three types:

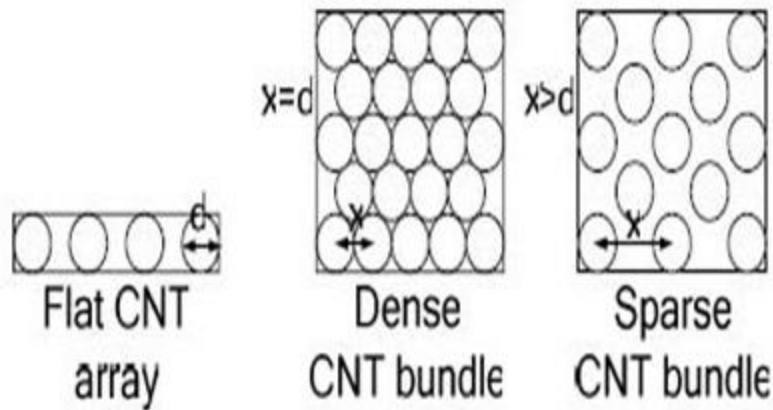


Fig. 1.9. Different arrangement of CNTs in the bundle [15].

Performance of CNT bundle interconnects is better when compared with the flat arrays. It is not necessary that all CNTs are metallic in bundle. In dense CNT bundle all CNTs are densely packed without any spacing and distance between two CNTs are equal to the diameter of CNT whereas in sparse CNT bundle CNTs have spacing between them which we can assume equal to x where $x > d$ where x stands for spacing between interconnect and d stands for diameter of CNT [15].

1.7 Mixed CNT Bundle:

CNTs are combined parallel to form a bundle to reduce the overall resistance. However, a realistic CNT bundle contains a mix of Single walled carbon nanotubes (SWCNTs) and Multi walled carbon nanotubes (MWCNTs). Both SWCNT and MWCNT have its own advantage. SWCNT have high equivalent resistance but it reduces to very small value when it used in bundle. MWCNT have less inductance and capacitance when used in bundle. So if we used both in the bundle overall performance will lead to the best.

Based on the arrangements of different CNTs in a bundle, four possible physical structures of MCB are shown in Figs.1.10.(a), 1.10.(b), 1.10.(c) and 1.10.(d). Each structure of MCB consists of multiwall and single wall CNTs. The first structure (MCB-1) of mixed CNTs is arranged in such a way that all the tubes which conduct maximum current are placed at centre of the bundle as shown in Fig.1.10.(a). The second structure (MCB-2) as shown in Fig.1.10.(b), demonstrates that all the tubes which conduct least or

no current are at middle of mixed bundle [16]. The primary advantage of MCB-1 is that the conduction mainly occurs through the tubes at centre of the bundle, while those at the outer periphery would serve as the shields from neighboring CNT bundles [17]. Each of these tubes (central or peripheral) can either be SWCNTs or MWCNTs. In MCB-3, shown in Fig.1.10.(c), the arrangement is made in a horizontal direction where MWCNTs are placed in the left half, while the SWCNTs are placed in the right half of the portion. However, in MCB-4 as shown in Fig.1.10.(d), the arrangement is made in the vertical direction where bottom half of the portion is filled by MWCNTs and the upper half is filled by SWCNTs. In this analysis, metallic CNT is considered as interconnect due its desirable properties and semiconducting CNT is ignored [18-20].

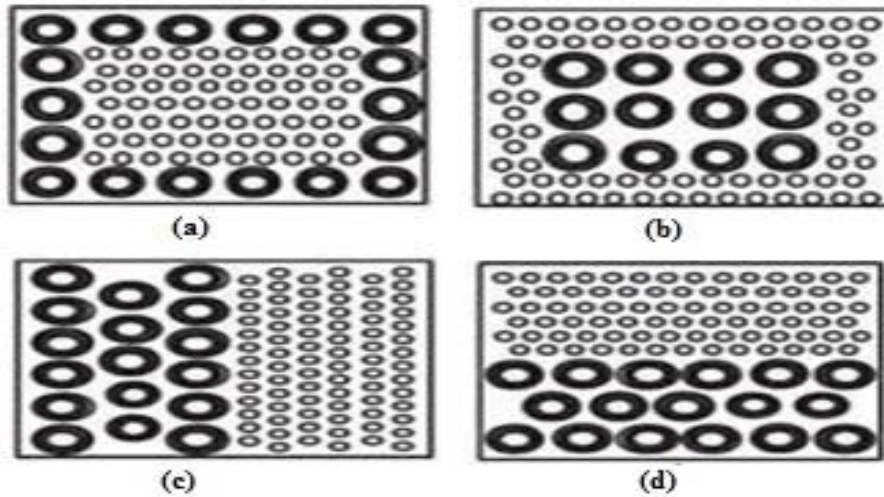


Fig.1.10. Different structures of mixed CNT bundle (a) MCB-1 (b) MCB-2 (c) MCB-3 (d) MCB-4.

1.8 Statement of the Problems:

The objectives of the research work presented in this thesis are as follows:

- Development of temperature dependent impedance parameter of Mixed CNT bundle based interconnects.
- Study the effect of temperature variation on Crosstalk noise analysis in mixed CNT bundle interconnects.

- Comparison of results obtained from the above analysis with results for Mixed CNT bundle and copper at 22nm technology node.

1.9 Organization of Thesis:

In this report the **Chapter 1** is an introduction to VLSI interconnect, interconnect material and CNT based VLSI interconnect. Recent advancements in this field are discussed. A brief discussion on the previously used interconnect, problems with existing interconnect material and then why CNT is preferable over the existing interconnects is included. This chapter also includes brief introduction about types of CNT based on geometry and based on layers, CNT bundle. Advantages of MCB is also discussed. Four structures are described in the MCB which is under analysis and all the results are given on basis of these four structures.

Chapter 2 covers the reviews of literatures that were used as reference during the research work in chronological order. In the last few years, defect free, SWCNT bundles are being used instead of Copper as VLSI interconnects in deep submicron technology nodes. However a realistic CNT bundle contains a mix of SWCNTs and MWCNTs. The growing density of integrated circuits with down scaling of technology, produce more transient crosstalk coupling among interconnects. As the technology is scaled down beyond a 45nm technology node, temperature of interconnects increases due to increase in resistivity of metal. So a lot of research work has been done on temperature dependent crosstalk analysis of SWCNT and MWCNT based interconnects but no study has been made to investigate the temperature-dependent crosstalk analysis in coupled interconnects of MCB. Thus, there is an important need to study the temperature-dependent crosstalk analysis in MCB interconnects.

Chapter 3 covers modeling of the MCB and copper based interconnects. All the parameters are calculated for both SWCNT and MWCNT and then combined to calculate the parameters for the MCB. Two cases are considered case-1 and case-2 in which case-1 considers coupling and tunneling effect whereas case-2 doesn't considers coupling and

tunneling effect. Similarly for copper also calculated all temperature dependent electrical parameters.

Chapter 4 covers the impedance analysis of MCB and copper based interconnects. As impedance directly affects the performance of interconnects so impedance of MCB for all structures is compared with the copper based interconnects and found that impedance of MCB fulfills the current technology requirements and can be alternative of the existing interconnects.

Chapter 5 covers the temperature dependent transient response of the Copper and MCB interconnects under both cases. With rise in temperature, how it affects the crosstalk voltage peak and crosstalk noise duration, discussed in this chapter. Temperature dependent transient response is discussed for all the four structures of MCB under both cases.

Chapter 6 covers the comparison of mixed CNT based interconnects with the copper. After calculating parameters calculated the crosstalk voltage peak and duration for all the structures of MCB under both cases and for copper, comparison of performance analysis of MCB under case-1 with copper interconnect is done. Also comparison of performance analysis for all the structures of MCB under both cases are done in this chapter.

Chapter 7 covers conclusion for all the chapters and then the final conclusion of all chapters. Suggestions for future work are also discussed in this chapter.

Chapter 2

Crosstalk Analysis – A Review

2.1 Introduction

Earlier aluminium was used as the interconnect material but due to less current carrying capability and low melting point, it was replaced by copper. Copper has advantages over aluminium like better current carrying capacity, high melting point and low resistance. But as the technology is going advance, interconnect width is reducing, causing surface scattering and electro migration which further increase propagation delay and crosstalk induced voltage noise. So according to the current technology demand, alternate of copper interconnect is needed which should fulfill all the requirement. In 1991, CNTs were discovered by Sumio Iijima, which are made up of graphene sheets rolled up into cylindrical form. The intrinsic resistance of an CNT is very high, but it can be reduced by using parallel tubes in a bundle for use as VLSI interconnects.

As the technology is scaled down beyond 45nm technology node, due to Joule heating, temperature of interconnects increases further increases resistivity of metal. So temperature dependent performance analysis of the interconnect is very important. A lot of research has been done for the temperature dependent analysis of SWCNT and MWCNT individually. But both SWCNT and MWCNT have their own advantage. So if we used both in the bundle overall performance will lead to the best. However no analysis has been made to analyze temperature dependent performance analysis for coupled MCB based interconnects. So in this thesis mainly focus is on the temperature dependent analysis of MCB interconnects.

2.2 Interconnect Performances

K. Bannerjee et. al. [1] examined the state-of-the-art in CNT research and discussed both the advantages and the problems in the new technology. As the resistivity of the copper is increasing with scaling and also a huge demand for the more current carrying

capability so there is a need of alternate of copper interconnect. They found that metallic CNT have the outstanding performance in conjunction with encouraging performance, thermal stability and high current carrying capability. So they concluded that metallic CNT are promising in future as it can overcome the problems facing by copper interconnect. Similarly **N.Srivastava et. al. [19]** discussed the application of the CNT as a future VLSI interconnect considering the practical limitations in the new technology. They developed a equivalent circuit model for the calculating parameters of CNT bundle based interconnect. Using this model they compared the performance of CNT bundle based interconnect with copper based interconnects. They found that performance of CNT as a local interconnect is not satisfactory as compared to copper interconnect. They further analyzed that there exists an optimal density less than the maximum density at which delay is minimum. Finally they concluded that CNT bundle can replace copper interconnect as intermediate or global interconnect but can be engineered to compete with copper as a local interconnect.

Naeemi et. al. [5] have discussed that for shorter interconnects the driver resistance is very high than interconnect resistance. So it is a dominant factor for the propagation delay. So to reduce the propagation delay it is must to decrease the interconnect capacitance. They have also shown that for the monolayer carbon nanotubes on a thick dielectric layer have capacitance 2 times smaller than copper wire. So it can be used as a shorter interconnect, as at that level driver resistance is quite dominant and latency is determined by capacitance. They have also shown that this is true only for carbon nanotube on thick dielectric layer not for thin dielectric layer and also not true for CNT bundle which has large capacitance as compared to copper wire. They have also told that as in CNT electrons can only move in one dimension so phase space for scattering is very limited, therefore they have large mean free path. They have also told that for large bias voltage electron back scattering effect is predominant and hence mean free path is less. They have also told that advantage of monolayer carbon nanotubes smaller capacitance can be taken if the driver size should be low because as aspect ratio is increased, driver resistance is decreased and become comparable with bundle resistance and hence in this case delay for copper wires will be less.

M.K. Rai and S.Sarkar [6] presented a exploratory research on CNT as possible future interconnect. The problems with the existing VLSI interconnect due to scaling and high current density, are briefly discussed. So there is a need to find an alternative of copper interconnect. They studied extensively the metallic SWCNT and found that isolated tube diameter has a important role in determining power dissipation and delay. Also interconnect length has important role. They also said that both SWCNT and MWCNT can replace copper interconnect as intermediate and global interconnect but at local level performance of copper is better. In [21], **M.K. Rai, Nivedita and S. Sarkar** have reviewed the work carried out to explore the applicability of CNT as future vlsi interconnects. In this paper they have described the equivalent model of SWCNT and SWCNT bundle and derived the formulae for impedance parameters. They have compared the performance of CNT bundle with copper interconnects and it is shown that for a densed bundle for interconnect length less than $1.6\mu\text{m}$, the propagation delay is worse than copper interconnects and it degrades with technology scaling, but in case of sparse bundle performance of CNT interconnect is better. They have shown that with increase in pitch for local interconnects delay increases, whereas for semi global and global interconnects the propagation delay is decreased by a large amount with respect to copper and relative delay become constant for global interconnects. They have also shown that the in semi global or global levels relative to copper, CNT performance improves with advancement of technology node. They have also reported that pitch influences semi global and global relative performance of CNT, so to achieve best performance of CNT interconnects, the pitch should be reduced as much as possible.

P. J. Burke [22] proposed a technique to directly excite Luttinger liquid collective modes in CNT at gigahertz frequency. He calculated the magnetic and kinetic inductance, fundamental resistance, electrostatic and quantum capacitance by modeling the nanotubes as a transmission line using [10]. He described a model for CNT using the concept of interacting electrons in one dimension. First he calculated the impedance parameters considering the spinless electrons. Then he compared the wave velocity for interacting electrons versus non-interacting electrons. He has also discusses two types of modes of channels in 1-D quantum wire- charge and spin mode.

Nisha Kuruvilla and J.P Raina [23] proposed CNT as a promising interconnect compared to copper interconnect in deep submicron IC technology. According to this literature most of literatures dealing with performance predictions of CNT interconnects, focused on only geometry of segregated CNTs. But during manufacturing step CNT obtained as the mixture of SWCNTs and MWCNTs. Specially in case of SWCNT, mixture of semiconducting and metallic CNTs are obtained. They compared the performance of CNT bundle containing segregated CNTs and the other is mixture of CNTs. Also a fix proportion of mix CNT is introduced in CNT bundle to yield a set of criteria to get optimum performance. They concluded that best performance was of metallic segregated SWNCT bundle with small tube diameter but the mixed bundle made of various combinations of CNTs had performance close to the best case performance.

Eric Pop et. al. [24] represented the first electro thermal analysis of SWCNT for interconnect application. They revealed that electron scattering by optical phonon absorption has considerable role in altering the low bias resistance of long SWCNTs while for shorter tubes, self heating at high bias must be taken into account. Also self heating in SWCNT interconnects can be avoided if power density per unit length is less than $5\mu\text{W}/\mu\text{m}$. In [25], **Eric Pop et. al.** discussed sources of uncertainty and propose a simple model for the SWCNT thermal conductivity including length and temperature dependence.

Y. Singh et. al. [26] analyzed the effect of driver size and number of shells on power and propagation delay for MWCNT based interconnects. They compared the delay and power for MWCNT and copper at different driver sizes and different number of shells. Results showed that propagation delay of MWCNT is lower than that of copper. Delay ratio of MWCNT to copper decreases with increase in length however delay ratio increases with reduction in number of shells in MWCNT. They concluded that in all the cases, power dissipation and delay of copper interconnect will always be more than that of MWCNT interconnect. **H. Li [27] et. al.** presented first time accurate analysis of MWCNT based interconnect performance. They presented a compact equivalent circuit model of

MWCNT and also compared the performance against traditional copper interconnect as well as with SWCNT interconnect. They concluded that MWCNT shows good improvement in signal delay compared to copper interconnect and it was predicted that improvement will be enhanced with the scaling whereas for local interconnect delay is marginally larger than the copper interconnect. When compared with SWCNT bundle interconnects, if SWCNT are 100% metallic and are densely packed then there is no extra benefit of MWCNT interconnect but if SWCNTs are of random chiralities and have low density then MWCNT bundle based interconnect can outperform the SWCNT bundle based interconnect.

As SWCNT and MWCNT based interconnect have its own advantages. So if we used both in the bundle the performance will lead to the best. So researcher focused more on the mixed CNT bundle. **P.K. Das et. al. [28]** introduced a new modeling approach for different types of CNT structure. They proposed two different structures of mixed CNT bundle based on the different arrangements of SWCNT and MWCNT. They observed that propagation delay primarily depends upon interconnect parasitic that can be calculated using the bundle geometry. On an average results showed that propagation delay is improved by 63% for the proposed structure in comparison to the structure containing equal halves of SWCNT and MWCNT interconnects located horizontally. Further **T. Alam et. al. [29]** have calculated the capacitance for mixed CNT bundle by first calculating the number of CNTs in the bundle (MWCNT and SWCNT). Then they observed the effect of diameter of CNT on capacitance which shows that with increase in diameter bundle capacitance increases but beyond a certain point capacitance starts decreasing. They have also observed the capacitance with respect to the probability of metallic tubes in the bundle. With increase in probability, capacitance increases because the number of channels per shell increases. They have also compared the capacitance of mixed CNT bundle with copper interconnects. For all types of interconnect capacitance of mixed CNT is smaller than capacitance of copper interconnects. They have concluded that the reduction in CNT bundle capacitance increases with downscaling. Therefore, mixed CNT bundle is a prospective alternative to copper for intermediate and global interconnects for very deep sub micron technology nodes.

W. Wang, S. Haruehanroengra, L. Shang and M. Liu [30] estimated the inductances of the mixed CNT bundle which are in agreement with current research results. They discussed different parameters such as tube density, metallic tube ratio, bundle dimension and tube distribution and their impact on the mixed CNT bundle with desirable inductance performance. Whereas **M.K. Majumder et. al. [31]** introduced an analytical model of mixed CNT bundle that follows the random distribution of CNTs. They presented a compact multi-conductor transmission line (MTL) and an equivalent single conductor (ESC) model based on the probability of distribution of CNTs having different diameters. They observed that performances are significantly improved for higher tube density. **L. Shang et. al. [32]** introduced compact current density models considering the effect of diameter and other structural factors. They analyzed various levels of improvement in realistic CNT densities over the copper wire. Similarly in **[33,34]** proposed accurate modeling approach for mixed CNT structures. SWCNTs and MWCNTs have been modeled as equivalent single conductor transmission line and then combined to form a mixed CNT bundles interconnect. They found that performance of mixed CNT bundle is superior to SWCNT or MWCNT bundles.

With the scaling of device current density is increasing causing Joule heating which further degrades the performance. So, temperature dependent analysis is important. **R. Verma et. al. [35]** addressed an analytical solution of the joule heating equation for metallic SWCNTs. They found that thermal conductivity increases slowly in the temperature profile along the length in case of pure SWCNT. However in case of impure SWCNT thermal conductivity reduces due to the presence of mass difference scattering which significantly raises the temperature. It has been found that increase in the form factor of the mass difference scattering severely raises the temperature rise along the length of SWCNT. Similarly **S. Bhattacharya et. al. [36]** also addressed an analytical model for temperature dependent thermal conductivity of metallic SWCNT. They proposed that thermal conductivity is dominated by boundary scattering at low temperature while at high temperature second order three-phonon process dominates the thermal conductivity.

Amir Hosseini and Vahid Shabro [37] presented an accurate thermally aware model for SWCNT based interconnects. Their thermally aware model considers temperature dependent electrical parasitic model and thermal equivalent circuit consisting both self heating and heat conduction phenomenon. They presented a simulation platform to estimate the performance of SWCNT based interconnects under the different temperature conditions. **A.G. Chiariello et. al. [38]** presented an electrical model for CNT based interconnect which includes in a meaningful way the effect of temperature changes. They found that GNR and MWCNT are much insensitive to temperature change than copper and SWCNT.

2.3 Crosstalk Analysis (Temperature-Independent)

As the interconnect density is growing and chip size is reducing, even the non- adjacent interconnect exhibit significant coupling effects due to which crosstalk noise is generated at the output. In recent time many of the researchers are focusing on the crosstalk noise as it is increasing day by day. **S.D. Pable et. al. [39]** examined and compared the effect of crosstalk on the delay for mixed wall CNT and for copper interconnects. They reported new aspect ratio for global interconnect to reduce the effect of crosstalk on interconnect performance. **Debaprasad Das and Hafizur Rahaman [40]** analyzed the effect of crosstalk in CNT interconnect and its impact on gate oxide reliability. From the existing model they calculated the parameters of SWCNTs and MWCNTs and developed a model to analyze the crosstalk. Overshoot/undershoot induced due to crosstalk have been estimated and the effect of overshoot/undershoot on the gate oxide in term of failure in time rate is calculated.

M.K. Majumder et. al. [41] presented a comparative analysis of performance based on delay and power between different bundled structures. They observed an average of 60 to 86% improvement in performance for the mixed CNT that contains equally halves of SWCNTs and MWCNTs compared to SWCNT bundles. **K. Aggarwal et. al. [42]** presented an analytical frame work to model crosstalk noise in coupled interconnects. They proposed a simple crosstalk noise model for the interconnects coupled on the chip. Their results showed that their model captured the accurate noise waveform and only

average error was just 6% for noise peak over many test cases. They found that crosstalk behavior is somewhat different in presence of inductive coupling as compared to in presence of purely capacitive coupling. So they concluded that traditional optimization solutions based on purely capacitive coupling would not be effective when both inductive and capacitive coupling would be between the interconnects on the chip.

In [43,44], B.K. Kaushik and S. Sarkar focused on the analysis of crosstalk of a CMOS gate driven capacitively and inductively coupled interconnect. They proposed a simple crosstalk noise model for coupled interconnects which are driven by CMOS gate as previously many researchers showed differences between analytical and simulation results. So proposed model estimated accurate noise in presence of inductive effects. **D. Rossi et. al. [45]** proposed novel bus architecture with low crosstalk features consisting DWNTs are in parallel. Crosstalk induced peaks and delays were reduced significantly using proposed architecture compared with previously presented CNT bus architectures. **M.K Rai et. al. [46]** estimated the crosstalk noise voltage levels in capacitive coupled SWCNT based interconnects. They proposed an improved model to find inter bundle real life coupling capacitance. They observed that victim line became more prone to crosstalk noise in copper as compared to CNT interconnect whereas noise peak voltage reduces with increase in interconnect capacitance.

2.4 Crosstalk Analysis (Temperature-Dependent)

As it has been already discussed that due to scaling Louis heating occurs causing increase in temperature. But electrical parameter are dependent on the temperature and a significant change can be noted in the parameters due to change in temperature which causes further change in crosstalk induced peak and delays. So from this prospective temperature dependent crosstalk analysis is very important. **M.K. Rai et. al. [47]** analyzed temperature dependent crosstalk induced noise voltage in coupled SWCNT based interconnect. Similar analysis was done for the copper based interconnects and the comparison was done for the both. They revealed that coupled SWCNT interconnects with increase in temperature filter more noise frequency components as compared to copper interconnects. **Lei Jia and Wen-Yan Yin [48]** proposed two modified equivalent

circuit models for SWCNT and DWCNT interconnects which are dependent on temperature and then effect of temperature on crosstalk in SWCNT and DWCNT interconnect are estimated.

2.5 Conclusion

Researchers analyzed the performance of CNT over the copper interconnect and consider as an alternative to the copper interconnect. From all above reviews it can be concluded that both SWCNT and MWCNT perform better than copper in semi global and global interconnect. MCB based interconnect can outperform both impure SWCNT and MWCNT interconnect as well as copper interconnect but it does not perform better than the pure metallic densely packed SWCNT bundle. So overall performance is much better for the MCB. Many researchers did work on crosstalk effects due to coupling and also found solution to optimize the performance. But a very few researchers presented work on temperature dependent crosstalk analysis for SWCNT or MWCNT interconnects and no work is done for MCB. So in this report temperature dependent crosstalk analysis for the different structures of MCB considering coupling of interconnects and tunneling effect is presented and the results are compared with the copper based interconnects.

Chapter 3

Temperature-Dependent Circuit Modeling of Mixed CNT Bundle

3.1 Introduction

Earlier researchers focused mainly on SWCNT and MWCNT interconnect applications. However after further research it has been proved that realistic nanotube bundles is the mixture of both SWCNTs and MWCNTs. So researchers focused on the MCB applications and gave many modeling models for calculating electrical parameters and also found impact of tube density, tube distribution, structure arrangement and bundle dimensions on the crosstalk induced peak and delay [48,49]. As discussed above, due to scaling, Joule heating occurs which further raises the interconnect temperature. Due to temperature variations, electrical parameters have a significant variations which further affects the performance of interconnects. So in section 3.2, an accurate model for temperature dependent modeling of MCB is given.

3.2 Temperature-Dependent Model

Geometrical structure is more complicated for MCB than that of SWCNTs and MWCNTs. So no direct analysis is possible for MCB interconnect. Therefore a new hierarchical model is developed [16] by assuming two different CNTs i.e. one SWCNT and other is MWCNT. For both SWCNT and MWCNT interconnects, equivalent single conductor (ESC) model has been developed. The equivalent circuit of each CNT is derived from Luttinger Liquid theory [22] and ESC models are developed for both SWCNT and MWCNT on the basis of transmission line theory [50,51]. So all these different interconnect model are merged to develop the MCB interconnect structure.

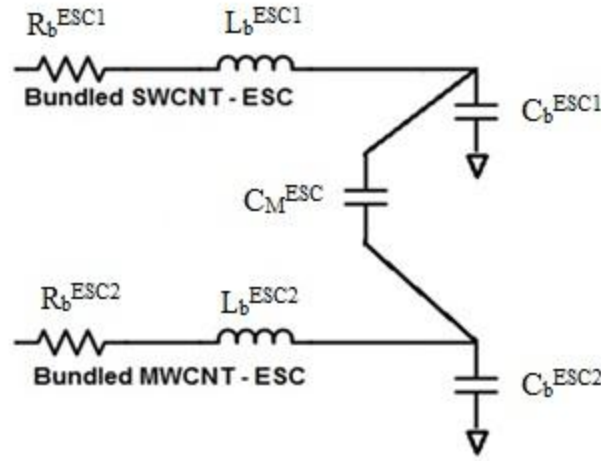


Fig. 3.1. Equivalent RLC model of mixed CNTs bundle based interconnects [16].

In Fig. 3.1, R_b^{ESC1} , R_b^{ESC2} , L_b^{ESC1} , L_b^{ESC2} , C_b^{ESC1} and C_b^{ESC2} are total equivalent resistance, equivalent inductance and equivalent capacitance of SWCNT bundle and MWCNT bundle, respectively. C_M^{ESC} is the coupling capacitance between the ESC of SWCNT bundles and MWCNT bundles. The coupling capacitance between two bundles has been obtained from [16, 20] and is given by Eq.(3.1),

$$C_M^{ESC} = \frac{\pi \epsilon_0 \epsilon_r}{\cosh^{-1}(\frac{S_p}{D'})} \quad (3.1),$$

where S_p is the distance between two equivalent bundled structures and D' is average diameter of SWCNT and MWCNT.

(a) R, L and C for an SWCNT Bundle: In order to model the resistance of metallic CNT interconnects. It is a critical need to investigate the different types and sources of temperature dependent scattering that influences the mean free path (λ) of CNTs. The equivalent distributed circuit model of an SWCNT interconnect is shown in Fig.3.2.

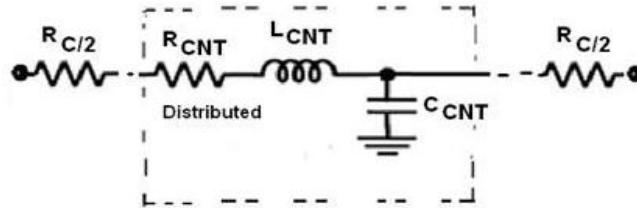


Fig.3.2. Equivalent distributed circuit model of an SWCNT [12].

The equivalent temperature dependent resistance of SWCNT bundle can be defined by using temperature dependent resistance of individual SWCNT ($R_{CNT}(T)$). This resistance consists of three components; contact resistance (R_C), quantum resistance (R_q) and scattering resistance (R_S). R_q and R_S are intrinsic resistance and R_C is due to imperfect contact between metal and semiconductor. The quantum resistance, $R_q = \frac{h}{2N(d,T)e^2}$, is the fundamental quantum of resistance and occurs if the length of nanotubes is less than MFP ($l < \lambda$). In such case ($l < \lambda$), electron transport within the nanotube is essentially ballistic, and resistance is independent of length. However, for length of nanotube is larger than MFP ($l > \lambda$), R_S occurs, as given by Eq.(3.2),

$$R_S = \frac{h}{2N(d,T)e^2} \left[\frac{l}{\lambda_{eff}(T)} \right] \quad (3.2),$$

where, R_S is the distributed scattering resistance, N is the number of available conducting channels in an SWCNT as a function of both tube diameter 'd' and temperature 'T', as given by Eq.(3.3) [37],

$$N(d, T) \simeq \begin{cases} 2 & \text{for } d < \frac{d_T}{T} \\ a \cdot d \cdot T + b & \text{for } d > \frac{d_T}{T} \end{cases} \quad (3.3),$$

Where $a \approx 6.12 \times 10^{-4} \text{ (nm K)}^{-1}$, $b \approx 1.275$, and $d_T \approx 1300 \text{ nm K}$ [1]. The scattering resistance of a nanotube is also bias dependent. At higher bias, CNT does not show ohmic behavior. While in the low bias regime, the CNT shows perfect ohmic behaviour and are compatible with VLSI interconnect applications. Therefore, the equivalent low bias temperature dependent resistance of SWCNT bundle is given by Eq. (3.4) [12,37].

$$R_b^{ESC1}(T) = \frac{R_{CNT}(T)}{N_{CNT}} \quad (3.4),$$

Where, N_{CNT} is total number of SWCNTs in bundle [19]. The resistance of an individual SWCNT with N conducting channel can be calculated by Eqs. (3.5) and (3.6),

$$R_{CNT}(T) = R_C + \frac{h}{2N(d,T)e^2} \quad (\text{for } l < \lambda) \quad (3.5),$$

$$R_{CNT}(T) = R_C + \frac{h}{2N(d,T)e^2} \left[\frac{l}{\lambda_{eff}(T)} \right] \quad (\text{for } l > \lambda) \quad (3.6),$$

Where, h is the Planck's constant, e is the electron charge, l is the length of interconnect. Here, for the sake of proper calculation of SWCNT resistance, R_C value is assumed to be $24 \text{ K}\Omega$ [15, 37].

It can be noted from Eqs. (3.4), (3.5) and (3.6) that the equivalent resistance of SWCNT bundle is a function of temperature-dependent effective MFP (λ_{eff}). It can also be noted that the value of MFP plays an important role in determining the resistance of the bundle. This includes scattering of electrons due to OP emission and absorption [24, 52]. The effective MFP of CNTs is a combined effect of all scattering lengths. This is due to the fact that the different scattering mechanism has different scattering lengths and dependent parameters viz., temperature, voltage bias, tube diameter and length. Hence, the effective temperature-dependent MFP is calculated by Eq. (3.7),

$$\frac{1}{\lambda_{eff}(T)} = \frac{1}{\lambda_{AC}} + \frac{1}{\lambda_{OP,abs}} + \frac{1}{\lambda_{OP,ems}} \quad (3.7),$$

Where, λ_{AC} is due to acoustic phonon scattering, λ_{abs}^{op} is due to scattering by non-polar optical phonon(absorption) and λ_{ems}^{op} is due to scattering by non-polar optical phonon(emission). MFP due to acoustic scattering is given by Eq.(3.8),

$$\lambda_{AC} = \lambda_{AC,300} \left(\frac{300}{T} \right) \quad (3.8),$$

MFP due to optical absorption and optical emission are given by Eqs. (3.9) and (3.10), respectively,

$$\lambda_{OP,abs} = \lambda_{OP,300} \left(\frac{N_{op}(300)+1}{N_{op}(T)} \right) \quad (3.9),$$

$$\lambda_{OP,ems} = (1/\lambda_{OP,ems}^{fld} + 1/\lambda_{OP,ems}^{abs})^{-1} \quad (3.10),$$

$$\lambda_{OP,ems}^{fld}(T) = \frac{\hbar\omega_{OP}}{e.Vdd} l + \frac{N_{op}(300)+1}{N_{op}(T)+1} \lambda_{OP,300} \quad (3.11),$$

$$\lambda_{OP,ems}^{abs}(T) = \lambda_{OP,abs}(T) + \frac{N_{op}(300)+1}{N_{op}(T)+1} \lambda_{OP,300} \quad (3.12),$$

Here, $\lambda_{AC,300}$ is the acoustic scattering length at 300K ($\sim 1600\text{nm}$), $\lambda_{OP,ems}^{abs}(T)$ is the OP emission MFP after absorption, $N_{op}(T) = \frac{1}{[\exp(\hbar\omega_{OP}/K_B T) - 1]}$, $\lambda_{OP,ems}^{fld}(T)$ is the former OP emission MFP event, $\hbar\omega_{OP}$ is the optical phonon energy ($\sim 0.18\text{eV}$) and $\lambda_{OP,300}$ is the spontaneous optical emission length at 300K ($\sim 15\text{ nm}$).

The other circuit parameters per unit length of metallic SWCNT bundle interconnect viz. Inductance and capacitance, are obtained from appropriate expressions available in [26-37, 46].

An isolated SWCNT has kinetic inductance (L_k) in addition to magnetic inductance (L_m). In a metallic SWCNT, the kinetic inductance (L_k) is the kinetic energy stored in each conducting channel of the CNT and depends on the net sum of the kinetic energy of left and right moving electrons in the nanotube, and, as a result, it is a per unit length quantity. Whereas, the magnetic inductance (L_m) captures the impact of the voltage induced by magnetic fields produced by time varying currents, which is encapsulated in Ampere's Faraday's laws and dependent on the entire current loop. The total inductance of an SWCNT bundle is the parallel combination of the L_k and L_m and obtained as in Eq. (3.13),

$$L_b^{ESC1}(T) = \left(\frac{L_m + (L_k/N)}{N_{CNT}} \right) \quad (3.13),$$

Where, L_m and L_k are the magnetic and kinetic inductances of an isolated SWCNT and calculated by Eqs. (3.14) and (3.15),

$$L_m = \frac{\mu}{2\pi} \ln\left(\frac{y}{d}\right) \quad (3.14),$$

$$L_k = h/(2e^2 v_f) \quad (3.15),$$

Where y is the height of an isolated SWCNT over a ground plane.

The capacitance of a SWCNT bundle consists of a quantum capacitance series with an electrostatic capacitance. The quantum capacitance is a per unit length quantity for a given nanotube. The electrostatic capacitance between adjacent nanotube bundles depends on the bundle geometry and spacing between bundles. The effective net capacitance of an SWCNT bundle is defined by Eq. (3.16), where C_E^{Bundle} and C_Q^{Bundle}

are the total electrostatic and total quantum capacitances per unit length of an SWCNT bundle and can be formulated by Eqs. (3.17) and (3.18) respectively,

$$C_b^{ESC1}(T) = \left(\frac{C_E^b \cdot C_Q^b}{C_E^b + C_Q^b} \right) \quad (3.16),$$

$$C_E^b = 2 \left(\frac{2\pi\epsilon_{ox}}{\ln(\frac{w}{d})} \right) + \left(\frac{[w-d-2]}{2} \right) \left(\frac{2\pi\epsilon_{ox}}{\ln(\frac{s+w}{d})} \right) + 3 \frac{(n_H-2)}{5} \left(\frac{2\pi\epsilon_{ox}}{\ln(\frac{s}{d})} \right) \quad (3.17),$$

$$C_Q^b(T) = \left(\left(\frac{2e^2}{h v_f} \right) N \right) N_{CNT} \quad (3.18),$$

Where, v_f is the Fermi velocity ($v_f = 8 \times 10^5$ m/s), n_H is the number of rows in the interconnect bundle, w is the width of SWCNT bundle, s is the separation between adjacent bundles, N is the number of available conducting channels in SWCNT, and d is the diameter of SWCNT.

(b) R,L,C for an MWCNT bundle: The MWCNT consists of concentric SWCNTs which are also called shells. An isolated MWCNT on an infinite ground plane and its equivalent distributed circuit model with n shells is shown in Fig.3.3 [27]. The number of channels of each shell is given by Eq. (5). The number of shells N_{shell} of the MWCNT and diameter of i_{th} shell are given by Eqs.(3.19) and (3.20), respectively [27],

$$N_{shell} = 1 + \left(\text{inter} \left\{ \frac{d_{max} - d_{min}}{2\delta} \right\} \right) \quad (3.19),$$

$$D_i = D_{max} - 2\delta(i-1), \text{ for } 1 \leq i \leq N_{shell} \quad (3.20),$$

Where “Inter{.}” indicates that only the integer part is taken into account. d_{max} is the diameter of outermost shell of an MWCNT, d_{min} is the diameter of innermost shell which generally has the value equals to $d_{max}/2$ and δ is the vanderwall gap(~ 0.34 nm). The temperature dependent effective mean free path of each shell will be same as that of an SWCNT and mean free path of each shell can be calculated by Eqs. (3.7) - (3.12).

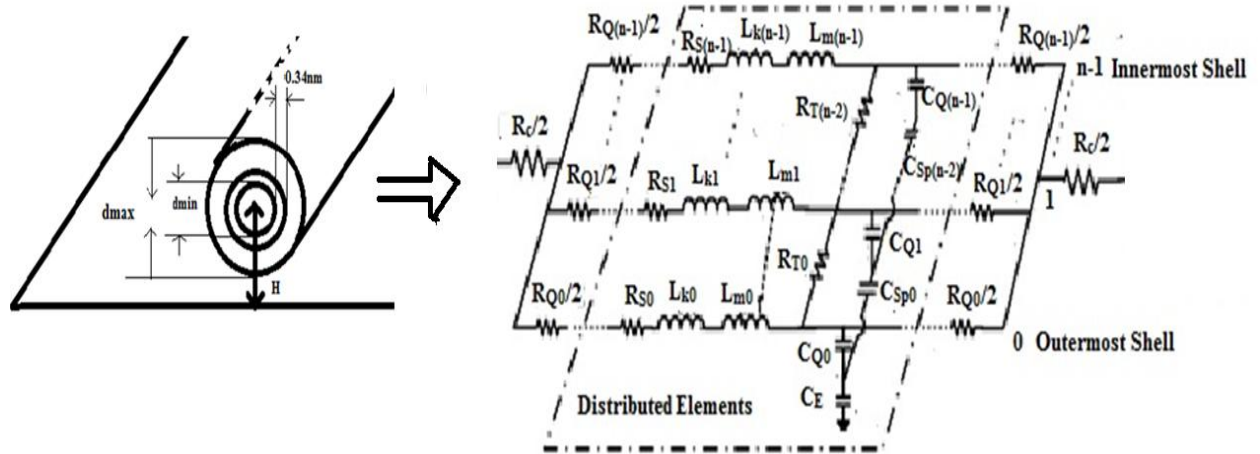


Fig. 3.3. Geometry of an MWCNT and its distributed circuit model [27].

An MWCNT has different diameters for different shells, which translate to different MFPs and channel numbers for each shell, resulting in different circuit parameters. Thus, the circuit parameters of each shell cannot be combined in to a simple way as similar to SWCNT bundles. The potential difference between adjacent shells in an MWCNT induces shell to shell capacitive coupling and tunneling effect [27]. Hence, in order to analyze the performance of MWCNT interconnects, intershell coupling and tunneling effects should be taken into account. The measured value of conductance between two adjacent shells has been reported, it is about $\sim(10\text{K}\Omega)^{-1}/\mu\text{m}$. In this present analysis, two cases of MWCNT are

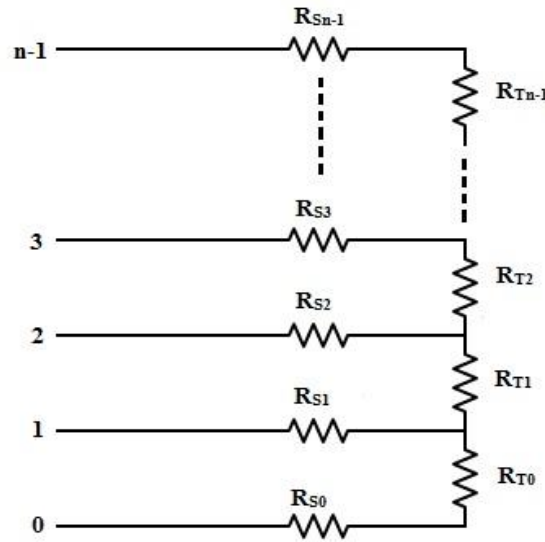


Fig. 3.4. Resistance network of an MWCNT.

considered; one in which tunneling effect and intershell capacitance can be taken in the equivalent circuit model [27] due to the interaction between shells ,and another case in which the interaction between shells in an idealized MWCNT is assumed to be negligible.

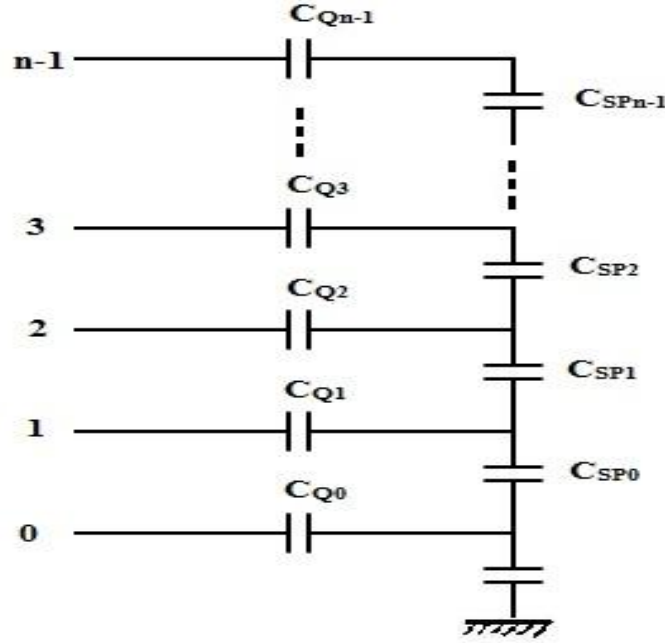


Fig. 3.5. Capacitance network of an MWCNT.

The impedance parameters, i.e., resistance(R) and capacitance (C) of an individual MWCNT can be derived by resistance and capacitance networks for 0 to $n-1$ shells as shown in Figs. 3.4 and 3.5, respectively. The resistance of each shell is given by the Eqs. (3.5) and (3.6) .It can be seen from Fig. 3.4 that the scattering resistance(R_s) of next shell is in parallel with series combination of tunneling resistance (R_T) and R_s of previous shell. So the total resistance of an MWCNT (R_{MWCNT}) is calculated by Eqs. (3.21) and (3.22),

$$R_{MWCNT}(T) = R_{x(k+1)} \quad (3.21),$$

where, $R_{x(k+1)}$ is calculated in a recursive way.

$$R_{x(k+1)} = (R_{x(k)} + R_{T(k)}) \parallel (R_{s(k+1)}) \quad (3.22),$$

Where, k depicts the shell number started from 0 to $n-2$, n is the total number of shells ($n \sim N_{\text{shell}}$), $R_{x(0)} = R_{s(0)} = R_{CNT}(T)$ is the resistance of each shell. The intershell tunneling conductance per unit length is obtained by Eq. (3.23) [27],

$$G_T = \sigma \cdot \pi D \quad (3.23),$$

Where, $\sigma = 0.3(\mu\Omega cm^2)^{-1}$ is the normalized tunneling conductivity at $\delta=0.34nm$ and is the shell diameter.

Hence, the total low bias temperature-dependent resistance of a bundle constituted by MWCNTs is calculated by dividing the resistance of an MWCNT by the number of MWCNTs .Which can be obtained by Eq.(3.24),

$$R_b^{ESC2}(T) = R_{MWCNT}(T)/n_{MWCNT} \quad (3.24),$$

$$n_{MWCNT} = \begin{cases} n_w n_h - (n_h/2) & \text{if } n_h \text{ is even} \\ n_w n_h - \left(\frac{n_h-1}{2}\right) & \text{if } n_h \text{ is odd} \end{cases} \quad (3.25),$$

Where, n_{MWCNT} is the number of MWCNTs in a bundle and calculated with the help of number of MWCNTs along the width and height,respectively.The number of MWCNTs along the width(n_w) and height(n_h), in four different physical structures of MCB for specific area covered by MWCNTs, are obtained by Eqs. (3.26) and (3.27),respectively.

$$n_w = \text{inter} \left[\frac{\text{width} - D}{D + \delta} \right] + 1 \quad (3.26),$$

$$n_h = \text{inter} \left[\frac{\text{height} - D}{\frac{\sqrt{3}}{2}(D + \delta)} \right] + 1 \quad (3.27),$$

The capacitance of an MWCNT has two parts; quantum capacitance (C_Q) and electrostatic capacitance (including inter shell capacitance (C_{SP}) and ground capacitance (C_E) [27]. Note that there is only one total ground capacitance associated with an MWCNT [27] in Fig. 3.5. This is because only the outermost shell has the electrostatic interaction with the ground, whereas the inner shells are shielded. So, the total equivalent capacitance of an MWCNT (C_{MWCNT}) is derived by capacitance network as shown in Fig.3.5 and modeled by Eqs. (3.28), (3.29) and (3.30)

$$C_{MWCNT} = \left[\frac{1}{C_{x(k+1)}} + \frac{1}{C_E} \right]^{-1} \quad (3.28),$$

Where, $C_{x(k+1)}$ is calculated in a recursive way.

$$C_{x(k+1)} = \left[\left(\frac{1}{C_{x(k)}} + \frac{1}{C_{SP(n-2-k)}} \right)^{-1} + C_{Q(n-k-2)} \right] \quad (3.29),$$

$$C_{x(n-1)} = \left[\frac{1}{C_{x(n-2)}} + \frac{1}{C_{SP(0)}} \right]^{-1} + C_{Q(0)} \quad (3.30),$$

Where, k depicts the shell number, n is the total number of shells ($n \sim N_{\text{shell}}$) and $C_{x(0)} = C_{Q(0)} = C_{Q(n-1)} = C_Q$ is quantum capacitance the per unit length of each shell. C_Q and C_{SP} per unit length are determined by Eqs. (3.31) and (3.32) [27],

$$C_Q(T) = \left(\left(\frac{2e^2}{h v_f} \right) N \right) \quad (3.31),$$

$$C_{SP} = \frac{2\pi \epsilon_0 \epsilon_r}{\ln\left(\frac{D_{out}}{D_{in}}\right)} = \frac{2\pi \epsilon_0 \epsilon_r}{\ln\left(\frac{D_{out}}{D_{out} - 2\delta}\right)} \quad (3.32),$$

Where, N is the number of conducting channel in each shell, D_{out} and D_{in} are the diameter of the outer and inner shells, and $\delta = 0.34\text{nm}$. The inter shell capacitance (C_{SP}) is similar to the electrostatic interaction between ground and outermost shell (C_E).

The total temperature dependent capacitance per unit length of an MWCNT bundle ($C_b^{\text{ESC}2}$) is calculated by Eqs. (3.25) and (3.28) - (3.32).

For an MWCNT, there are magnetic inductance and kinetic inductance per shell. The total temperature dependent inductance per unit length of a bundle constituted by MWCNTs is given by Eq. (3.33) [27],

$$L_b^{\text{ESC}2}(T) = \left(\frac{L_m + (L_k/N)}{N_{\text{shell}} \cdot n_{\text{MWCNT}}} \right) \quad (3.33),$$

Where, L_m and L_k are the magnetic and kinetic inductances per shell of an MWCNT and calculated by Eqs. (3.14) and (3.15), respectively. Here, the mutual inductance is neglected from the inductance model of an MWCNT. This is due to fact that the mutual inductance is much smaller than the kinetic inductance of each shell [27].

Based on the aforementioned analysis regarding the modelling of temperature-dependent circuit parameters, equivalent circuit parameters per unit length for the ESC model of MCB are given by Eqs.(3.34) - (3.36) by,

$$R_{ESC}(T) = R_b^{ESC1}(T) \parallel R_b^{ESC2}(T) \quad (3.34),$$

$$L_{ESC}(T) = L_b^{ESC1}(T) \parallel L_b^{ESC2}(T) \quad (3.35),$$

$$C_{ESC}(T) = \left(\frac{C_b^{ESC1}(T) \times C_M^{ESC}}{C_b^{ESC1}(T) + C_M^{ESC}} \right) \parallel C_b^{ESC2}(T) \quad (3.36),$$

Where, R_b^{ESC1} , L_b^{ESC1} and C_b^{ESC1} are resistance, capacitance and inductance of an SWCNT bundle, and R_b^{ESC2} , L_b^{ESC2} and C_b^{ESC2} are resistance, capacitance and inductance of an MWCNT bundle.

Copper: To estimate the performance of copper interconnects accurately under temperature variation, the interconnect is replaced by a solid metal of same dimensions. The following temperature-dependent low bias resistance formula can be used [12, 15].

$$R(T) = R_0[1 + \alpha(T - T_0)] \quad (3.37),$$

Here, $\alpha = 0.0039K^{-1}$ is the temperature coefficient of resistance measured at room temperature [15]. R_0 is the resistance at room temperature, defined as $R_0 = \frac{\rho_0 L}{A}$. Here, ρ_0 is the resistivity of copper at room temperature [22]. In order to calculate the other temperature-independent circuit parameters of copper, the following analytical expressions are used [12,15,27,40].

$$L_s = \frac{\mu_0 l}{2\pi} \left[\ln \frac{2l}{w+t} + 0.5 + \frac{0.22(w+t)}{l} \right] \quad (3.38),$$

$$C_g = \epsilon \left[\frac{w}{d} + 2.22 \left(\frac{s}{s+0.7d} \right)^{3.19} + 1.17 \left(\frac{s}{s+1.15d} \right)^{0.76} \left(\frac{s}{H+4.53d} \right)^{0.12} \right] \quad (3.39),$$

$$C_c = \epsilon \left[1.14 \frac{t}{s} \left(\frac{d}{d+2.06s} \right)^{0.09} + 0.74 \left(\frac{w}{w+1.59s} \right)^{1.14} + 1.16 \left(\frac{w}{w+1.87s} \right)^{0.16} \left(\frac{d}{d+0.98s} \right)^{1.18} \right] \quad (3.40),$$

Here, L_S is the self inductance, C_g is the capacitance with respect to ground, C_C is the coupling capacitance between adjacent interconnects, l = length, w = width, t = thickness, d = height above ground, s = spacing, ε = dielectric constant and μ_0 = permeability.

3.3 Conclusion

Geometrical structure is more complicated for MCB than that of SWCNTs and MWCNTs. So no direct analysis is possible for MCB interconnect. For both SWCNT and MWCNT interconnects, equivalent single conductor model has been developed. All these different interconnect model are merged to develop the MCB interconnect structure considering the effect of coupling and tunneling effect. It is found that performance of MCB interconnect leads to the best.

Chapter 4

Temperature-Dependent Impedance Analysis

4.1 Introduction

In this section, temperature-dependent impedance analysis is presented for different structures of MCB and copper based interconnects at 22nm technology node, respectively. Due to the change in temperature, variations in impedance are significant which are necessary to be studied. Physical parameters are taken from the latest interconnect geometry predicted by ITRS-2012 [53]. The temperature dependent circuit parameter of MCB interconnects are calculated under two different cases (with and without tunneling and intershell coupling effects).

4.2 Impedance Analysis

It has been found in [27] that the tunnelling conductance and intershell coupling have a significant impact on the performance of MWCNT bundle as compared to ideal case (the interaction between shells in an idealized MWCNT is assumed to be negligible). Hence, for the sake of accurate circuit modeling of MCB that consists of SWCNTs as well as MWCNTs, tunneling effects and intershell coupling are considered. The circuit parameters (R, L and C) of copper are calculated using appropriate expressions available in [12,15,40,53,54] at 22nm technology node.

Table 4.1. Simulation Parameters [ITRS 2012].

S. No.	Parameters	Values
1.	Technology node	22 nm
2.	$\epsilon_{ox}(\text{relative})$	3.25
3.	A/R of interconnect(Global)	2.34
4.	Separation(s) between adjacent bundle of global interconnects	29 nm
5.	Width(w) of global interconnect	29 nm
6.	Thickness(H) of interconnect	68 nm
7.	Oxide Thickness	43.5 nm

8.	$\rho_{cu}(\mu\Omega\text{-cm})$ of global interconnect	5.26
9.	Minimum Sized Gate $R_{dr}(K \ \Omega)$	16.47
10.	Minimum Sized Gate $C_L(fF)$	0.35

As may be observed from previous section, the low bias resistance of both MCB and copper is a function of temperature dependent mean free path of electrons; while equivalent inductance and capacitance are the function of temperature dependent number of conducting channels in carbon nanotube.

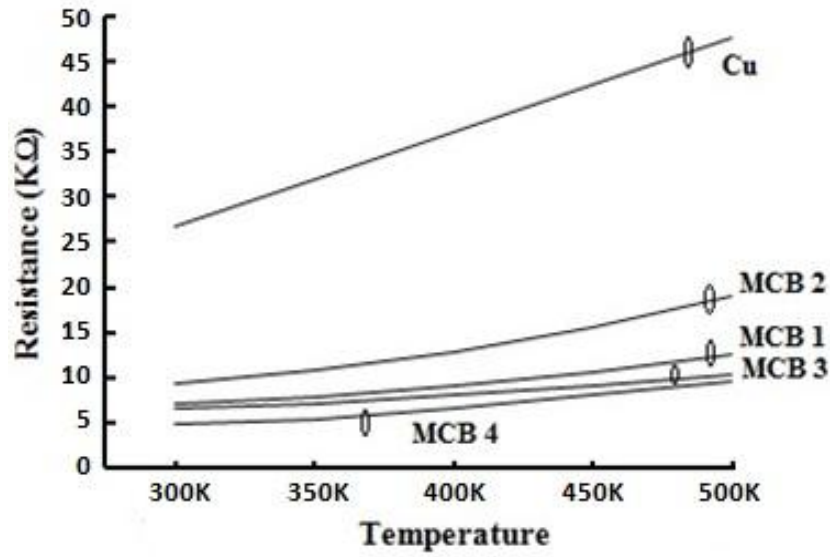


Fig. 4.1. Variation of resistance for different structures of mixed CNT bundles with copper as a function of temperature considering tunneling effect and shell to shell capacitance.

In Fig.4.1, the variation of low bias resistance of 1mm long interconnect as a function of temperature, ranging from 300K to 500K, is exhibited for different structures of MCBs and copper, respectively. It is observed that the resistance increases with rise in temperature for all structures of MCBs and copper based 1mm long interconnects. However, the resistance of copper interconnect, at any specific temperature, in the range 300K to 500K, is several times larger than that of all four structures of MCBs. This is because of weak variation of temperature dependent scattering on the mean free path of carbon nanotube electrons as compared with that of copper counterpart.

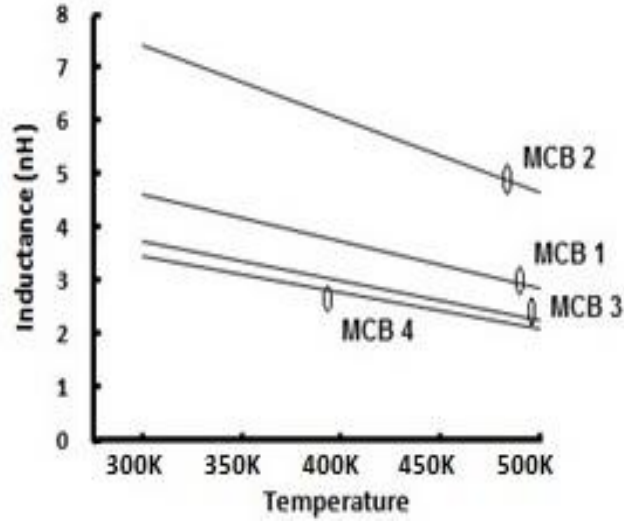


Fig.4.2. Variation of inductance as a function of temperature for different structures of MCBs.

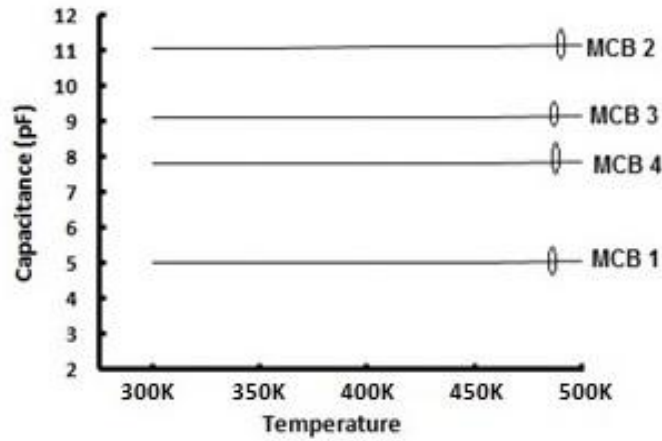


Fig.4.3. Variation of capacitance as a function of temperature for different structures of MCBs.

Figs. 4.2 and 4.3 illustrate the dependence of inductance and capacitance on temperature for different structures of MCBs, respectively. This is an example of the dependence of MCB interconnect inductance and capacitance on temperature-dependent number of conducting channels. It can be seen that the inductance decreases rapidly with rise in temperature for all structures of MCBs. This is due to the fact that the impact of temperature-dependent kinetic inductance, compared with temperature-independent magnetic inductance, is more in an equivalent inductance of MCB interconnect. On the other hand, temperature variation has negligible effect on capacitance of different structures of MCBs due to the dominance of intershell

capacitance over temperature dependent quantum capacitance in an equivalent capacitance of MCB interconnect. However, as may be seen from Eqs. (38) and (39), the equivalent inductance and capacitance of copper interconnect are the temperature-independent parameters. The calculated values of temperature-dependent circuit parameters using case-1(with tunnelling effect and intershell coupling) and case-2(without tunnelling effect and intershell coupling) show distinctive feature (Tables 4.1 and 4.2) at 300K. In comparison with values of temperature-dependent circuit parameters using case-1, the values of temperature-dependent circuit parameters using case-2 are less for four different structures of MCBs.

Further, it may also be noted that, in the context of reducing voltage noise levels and time duration of output transient response, compared with copper interconnects, MCB based interconnects are more promising in advanced technology nodes.

Table 4.2. Impedance parameters of 1mm long interconnect at temperature 300K without tunneling & shell to shell coupling , technology = 22nm.

S. No.	Impedance Parameters	Different structures of mixed CNT bundle				Copper
		MCB 1	MCB 2	MCB 3	MCB 4	
1.	Resistance ($K\Omega$)	4.95	5.35	5.98	4.69	26.67
2.	Ground Capacitance (pF)	2.31	2.3	2.3	2.31	5.74
3.	Self Inductance (nH)	4.61	7.38	3.73	3.45	2.09
4.	Coupling between interconnects (fF)	94.1				

Table 4.3. Impedance parameters of 1mm long interconnect at temperature 300K with tunnelling & shell to shell coupling , technology node = 22nm.

S. No.	Impedance Parameters	Different structures of mixed CNT bundle			
		MCB 1	MCB 2	MCB 3	MCB 4
1.	Resistance ($K\Omega$)	6.35	9.2	6.4	5.8
2.	Ground Capacitance (pF)	5.02	11	9.13	7.83
3.	Self Inductance (nH)	4.61	7.38	3.73	3.45
4.	Coupling between SWCNT & MWCNT bundle in MCB (pF)	0.103	0.51	0.34	0.362

Most investigators of carbon material based interconnects assume the value of coupling capacitance as equivalent to that of the coupling effect between metal interconnects of the same dimensions [12,40,45]. Based on this theory, coupling capacitance of MCB interconnect is assumed to be same as that of copper based interconnect with same dimensions. Hence, the value of coupling capacitance between adjacent interconnects of MCB and copper is calculated by Eq. (40) and tabulated in Table 4.2 at 22nm technology node.

4.3 Conclusion

In this chapter resistance, inductance and the capacitance of the different structures of MCB is compared with the copper based interconnects. The resistance of MCB is very less than that of copper interconnect for entire range of temperature between 300K to 500K. As temperature increases inductance of MCB decreases whereas the capacitance seems to be constant for whole range of temperature. In comparison with values of temperature-dependent circuit parameters using case-1, the values of temperature-dependent circuit parameters using case-2 are less for four different structures of MCBs.

Chapter 5

Thermally Aware Crosstalk Analysis in Coupled Mixed CNT Bundle Interconnects

5.1 Introduction

As discussed in earlier sections carbon nanotube interconnects can be considered as ideal interconnects for deep submicron technology. The serious crosstalk problem due to coupling has not been analyzed yet it is known that effect of coupling on the MCB is not significant in comparison to copper interconnect. For conventional interconnects crosstalk causes the signal delays, glitches which are significant and cannot be ignored. If the glitch caused by crosstalk is more than that of threshold voltage than it will be wrongly interpreted at the output. In this section crosstalk effects are analyzed for different structures of MCB with and without coupling effects and tunneling resistance and the results are compared with copper based interconnects.

5.2 Temperature-Dependent Performance Analysis

With growing interconnect density and reduced chip size, even the non-adjacent interconnects exhibit significant coupling effects. So, Coupled voltage can be separated into two classifications: (i) functional crosstalk noise and (ii) dynamic crosstalk noise. In functional crosstalk noise, a victim line experiences a voltage spike due to nearby line (aggressor) switching; though the second issue that happens in the coupled lines is because of the synchronous switching either in phase or out of phase. Crosstalk in capacitively coupled interconnects may induce delay, logic failure, and noise in the victim line.

It is evident from aforementioned discussion in above sections that the temperature dependent mean free path controls the circuit parameters of MCB. Thus, it is important to investigate the temperature-dependent performance of MCB interconnects. In this section, the temperature-dependent, crosstalk- induced voltage waveform at the far end of

victim line, in capacitively coupled MCB interconnects, have been analyzed first time, at 22nm technology node. A similar analysis is performed for copper interconnects and a comparison is made between the results of these two analyses. Further, detailed investigations of positive voltage peaks and time duration of the victim output waveforms between MCB interconnects with temperature-dependent circuit parameters estimated (a) with tunneling effects and intershell coupling, and (b) without tunneling effects and intershell coupling, are presented.

As the integration density of interconnects increases with aggressive technology scaling; crosstalk effects will become increasingly valuable in a high performance integrated circuits [12,15,40,42-45]. These high performance integrated circuits have a great variance in temperature which have a significant effect on the crosstalk-induced voltage noise between coupled interconnects. However, no account of temperature dependent crosstalk induced voltage noise in coupled MCB interconnects has been reported. Hence, there is an essential need to study the temperature-dependent crosstalk-induced voltage noise in scaled deep sub-micron (DSM) CMOS technologies for MCB interconnects.

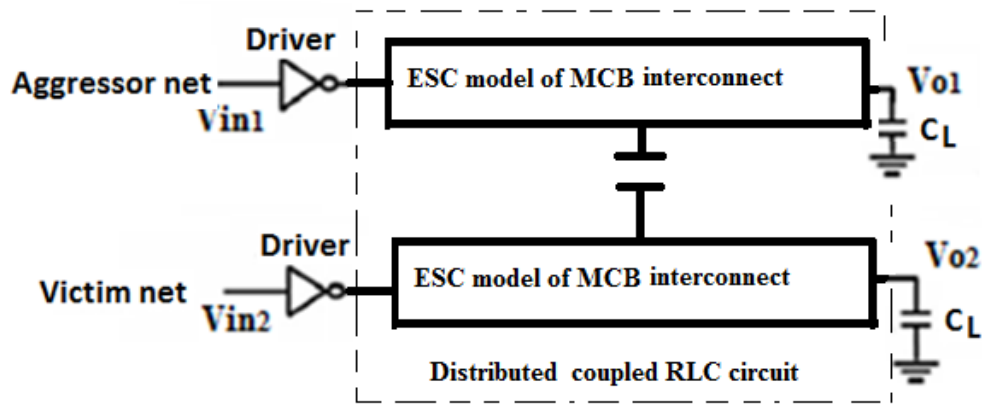


Fig.5.1. Distributed capacitively coupled RLC interconnect circuit [16].

To analyze the crosstalk voltage noise, a distributed capacitively coupled RLC interconnect circuit has been considered as shown in Fig.5.1. Each distributed interconnect RLC circuit in coupled interconnects is replaced by ESC model of the MCB interconnect, which is shown in Fig.3.1. All the signal wires are driven by a CMOS driver at 22nm technology node [54] with a clock speed of 0.1 GHz, $V_{dd} = 0.9V$, rise time = 1 ns, fall time = 1 ns, and terminated with capacitive load of 0.14fF [12,15,27].

For crosstalk analysis, the victim net (i.e. the crosstalk affected net) is kept fixed at logic 1 and the aggressor nets (i.e. the net that causes crosstalk on victim) are switched from logic 1→0. For all calculation and simulation purposes, the data shown in Table 1 have been used.

Figs.5.2-5.4 illustrate the crosstalk-induced transient responses of the victim output at different temperatures, for MCBs constituted in four different structures under case-1 and case-2, and copper interconnects respectively, and provide an insight into the temperature variation of interconnect circuit parameters (see Figs. 4.1, 4.2 and 4.3). It is observed that the transient variation of crosstalk-induced voltage noise levels decrease for both MCB and copper interconnects with rise in temperature from 300K to 500K. Whereas, reverse is true for the time duration of transient responses.

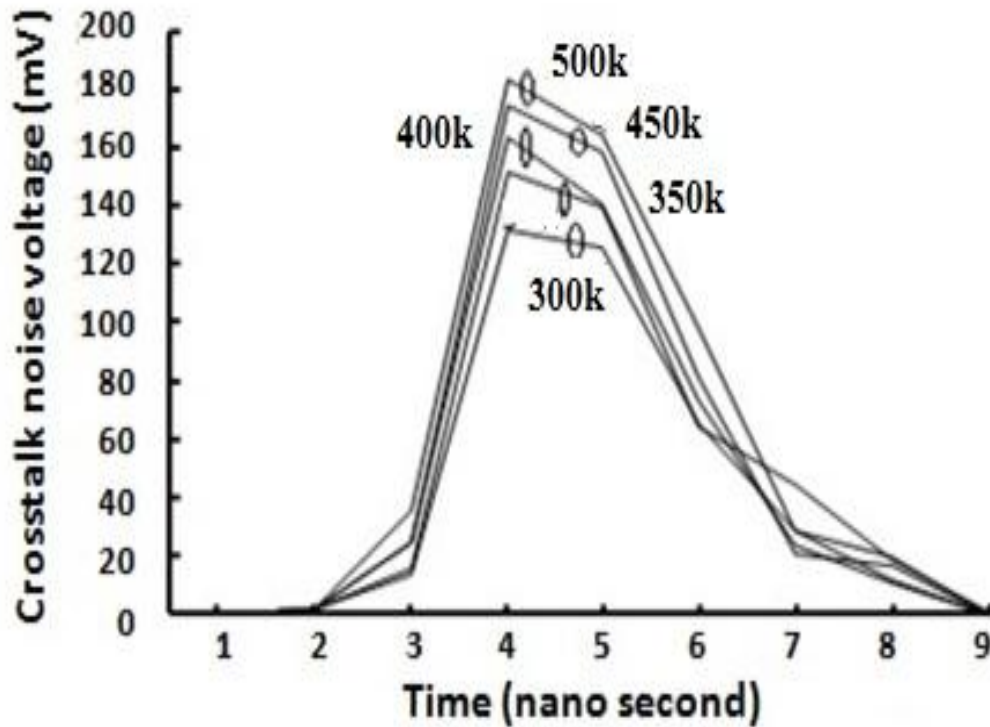


Fig 5.2. Crosstalk induced transient response of coupled interconnects for copper based interconnects at the far end of victim line at 22nm technology node for different temperature.

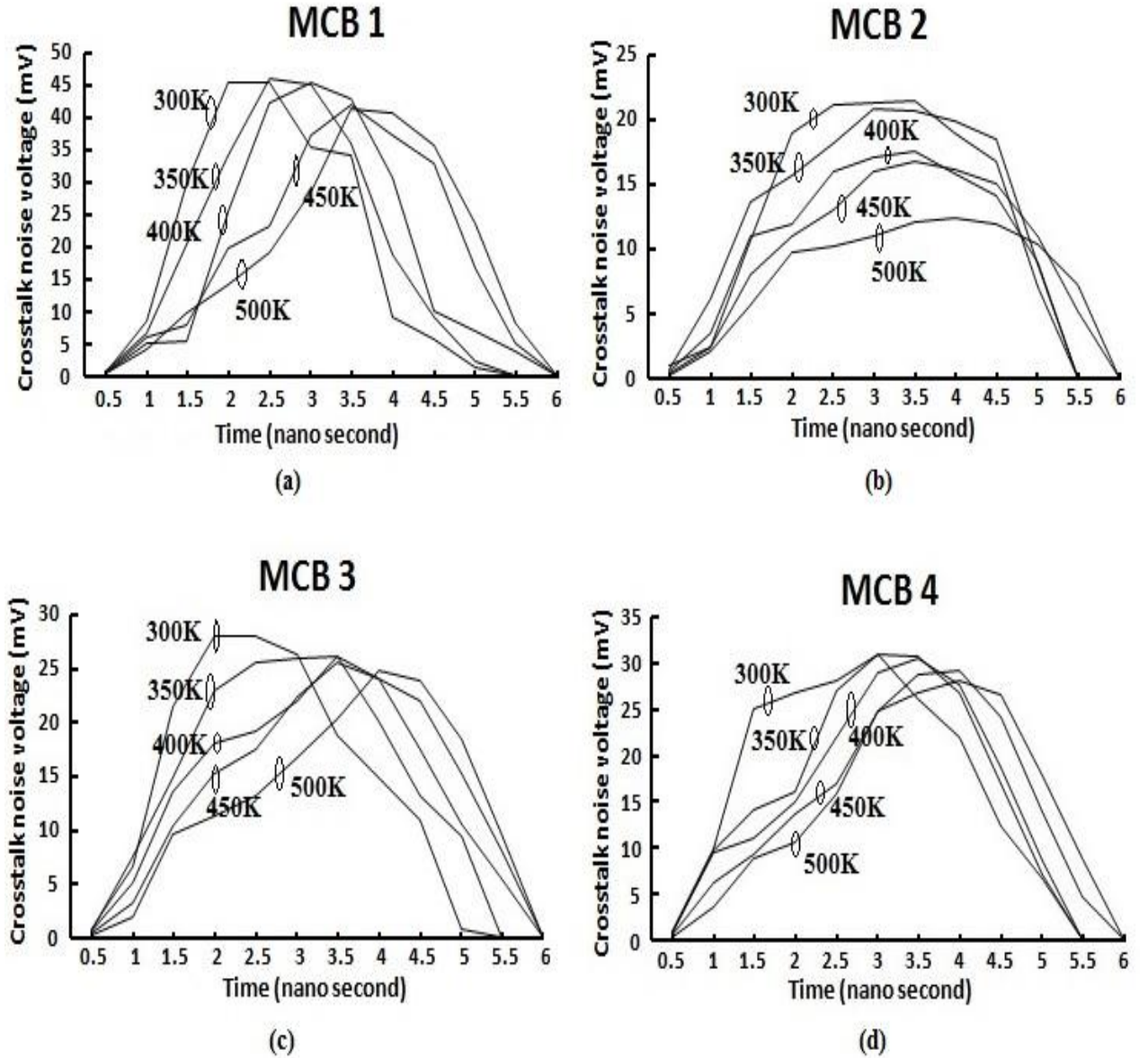


Fig. 5.3. Crosstalk Induced Transient Response of coupled interconnects with tunneling and shell to shell coupling for the (a) MCB 1 (b) MCB 2 (c) MCB 3 (d) MCB 4 at the far end of victim line at 22nm technology node for different temperature.

This is due to the combined effects of temperature dependent resistance and inductance on transient responses at the far end of victim line. It is found in [12,15,42,43], as resistance increases, the voltage steps arriving at the far end of the interconnect are smaller in amplitude and have larger time duration. While, the noise peak in terms of voltage noise level reduces with decrease in interconnect inductance (self inductance)

[42]. The distinctive features are also extracted from Figs.5.2-5.4 for the different structures of MCBs and copper.

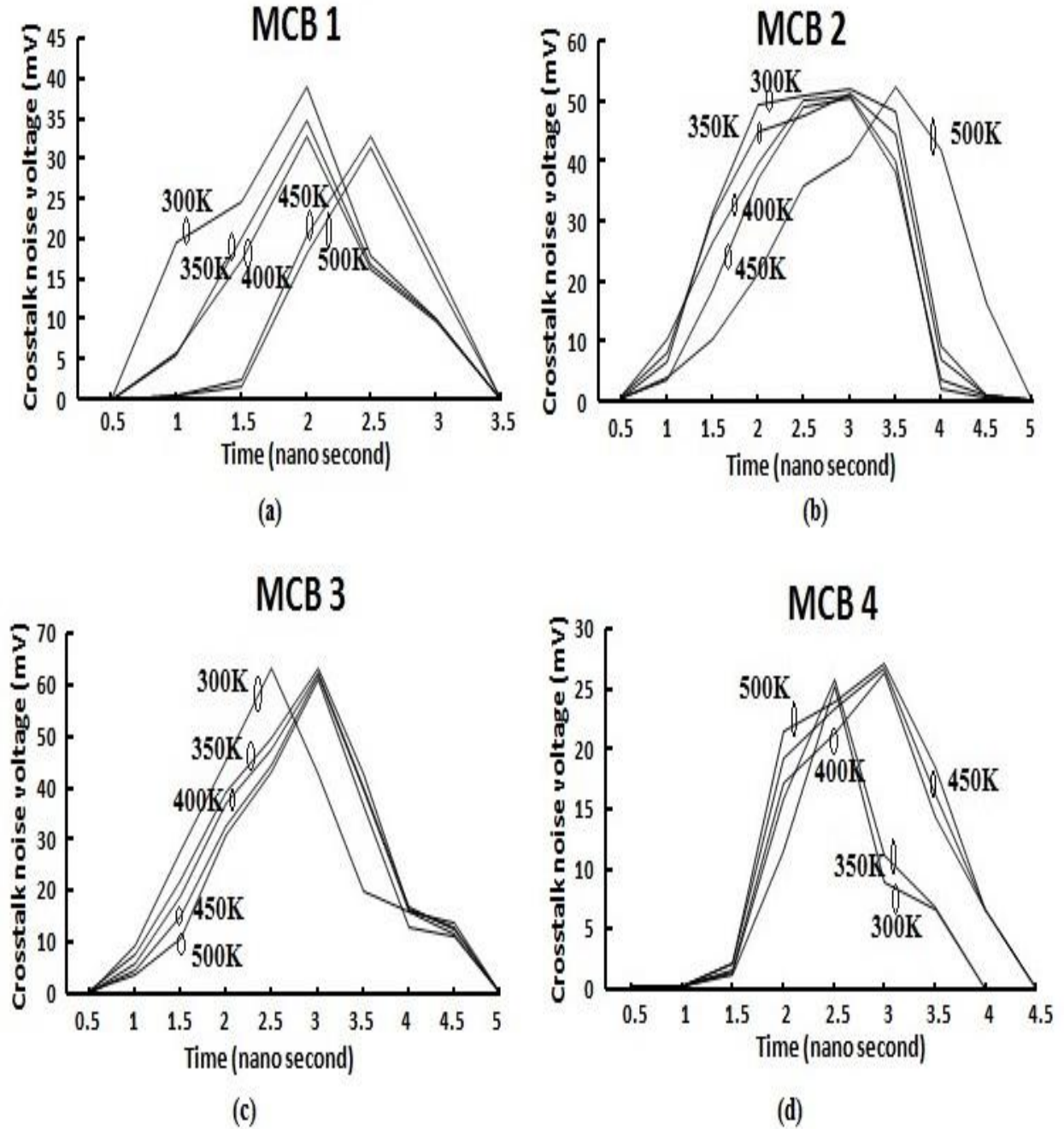


Fig.5.4. Crosstalk Induced Transient Response of coupled interconnects without tunneling and shell to shell coupling for the (a) MCB 1 (b) MCB 2 (c) MCB 3 (d) MCB 4 at the far end of victim line at 22nm technology node for different temperature.

5.3 Conclusion

In this chapter performance analysis is done for copper and MCB based interconnects. As temperature increases, the crosstalk noise voltage peak shifts to the right so duration of noise increases and the peak voltage decreases for MCB based interconnects. For copper the behavior is different, as both time duration and voltage peak increases with increase in voltage.

Chapter 6

Comparative Analysis Between Interconnects of Mixed CNT Bundles and Copper

6.1 Introduction

Copper is the most widely used interconnect material in current technologies but as the technology is going to be advanced, due to scaling many problems like electro-migration, grain boundary effect etc. are coming in the existing interconnect material. So there was strong need to find an alternative. So researchers found CNT interconnects as an alternative of copper. Both SWCNT and MWCNT have their own advantages. So, in MCB both these CNTs are combined and the performance is improved in comparison to SWCNTs and MWCNTs individually. So in this section a comparative analysis of MCB interconnects is done to analyze the improvement in performance in comparison with the Cu interconnects.

6.2 Comparative analysis between Copper and MCB Interconnects

Figs 6.1 and 6.2 show the dependence of positive noise voltage peaks on temperature for MCBs constituted in four different structures under case-1 and case-2, and copper at the far end of victim in capacitively coupled interconnects. It is observed that the MCBs constituted in four different structures under case-1 have smaller positive voltage peaks, at any specific temperature from 300K to 500K, compared with MCBs constituted in four different structures under case-2. This is due to the fact that the MCBs with case-1 have larger values of line resistance and capacitance at any specific temperature, ranging from 300K to 500K (Table 4.2 and 4.3). In comparison with MCB-1, MCB-3 and MCB-4 in case-1, the MCB-2 has lower positive peaks at any specific temperature, ranging from 300K to 500K, due to its higher value of line resistance and capacitance. On the other hand, in case-2, the MCB-4 has lower positive peaks among all structures of MCB due to dominance of self inductance over resistance and capacitance. It is noted, compared with

case-2 of MCBs, the victim line gets less prone to crosstalk noise in capacitively coupled interconnects of MCBs (case-1). It is also observed from Figs. 6.1 and 6.2 that, compared with its copper counterpart, at any specific temperature, in the range 300K to 500K, the MCB structures for case-1 and case-2 at the far end of victim line, have several times lower positive voltage peaks (voltage noise levels). This is because of lower temperature-dependent circuit parameters associated with four structures of MCB in case-1 and case-2 (Table 4.2 and Table 4.3).

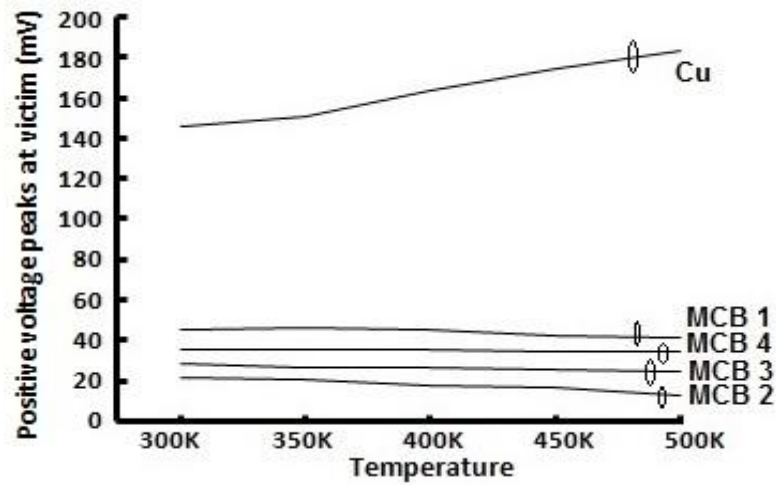


Fig. 6.1. Variation of positive voltage peak of MCBs constituted in four different structures under case-1 with variation in temperature.

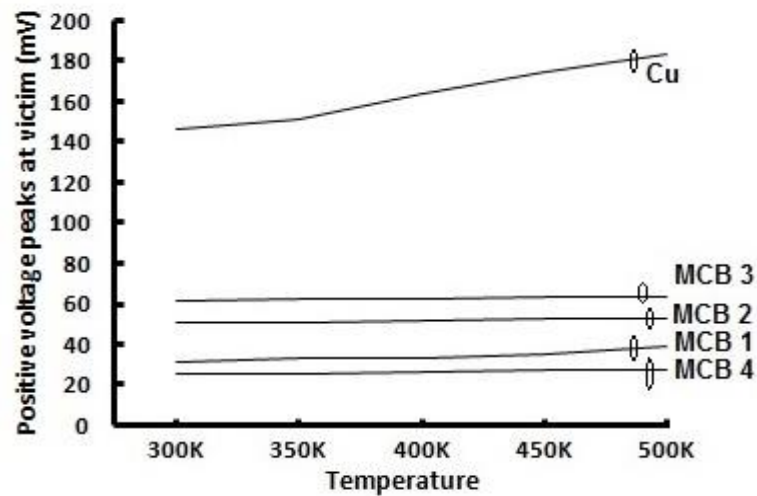


Fig. 6.2. Variation of positive voltage peak of MCBs constituted in four different structures under case-2 with variation in temperature.

Fig. 6.3 and 6.4 illustrate the dependence of time duration of the victim output waveform on temperature from 300K to 500K for different structures of MCB under case-1 and case-2, and copper.

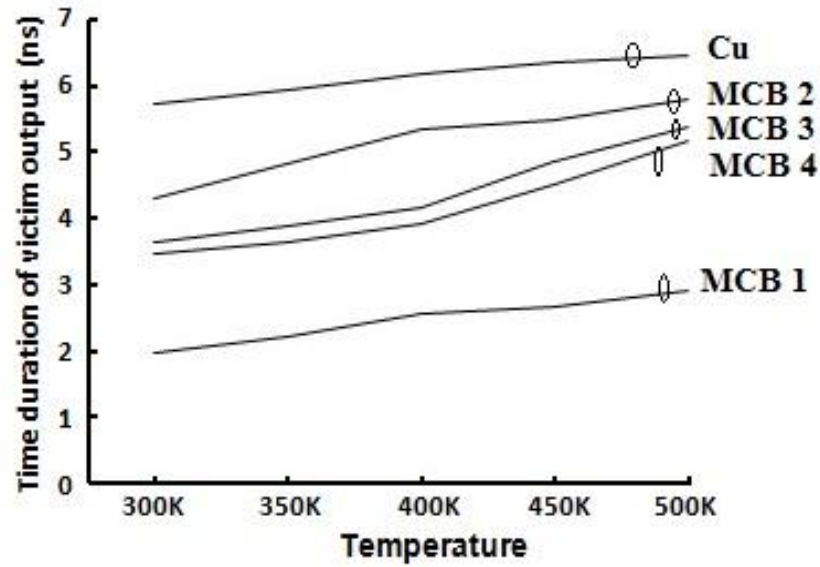


Fig.6.3. Variation of time duration of MCBs constituted in four different structures under case-1 with variation in temperature.

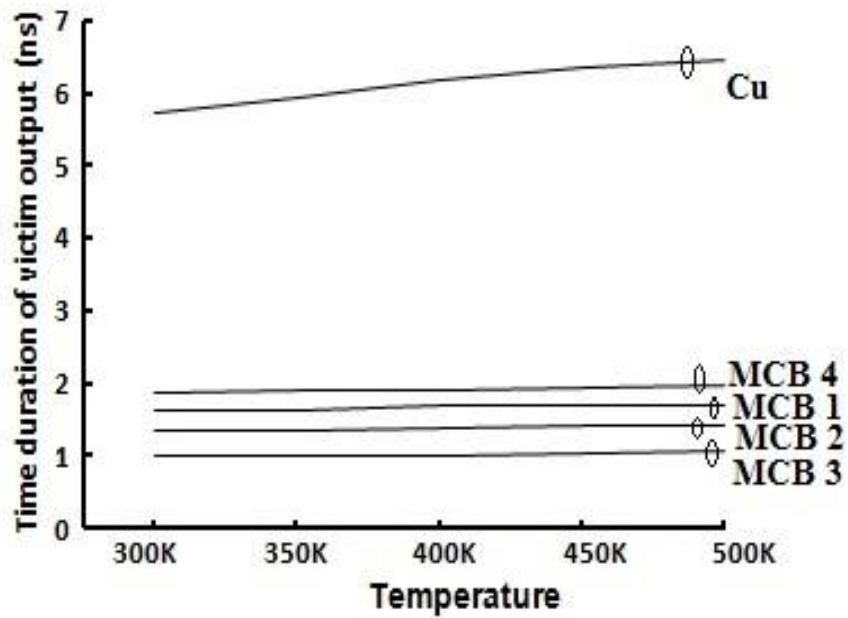


Fig.6.4. Variation of time duration of MCBs constituted in four different structures under case-2 with variation in temperature.

It is observed that the time duration of transient response at victim line gradually increases with rise in temperature, ranging from 300K to 500K, for both MCB and copper but this variation is observed to be more in copper as compared to MCB. The gradual rise of time duration indicates the dominance of line resistance and inductance over its capacitance with rise in temperature. This is due to the higher temperature-dependent circuit parameters associated with copper (Tables 4.2 and 4.3) as compared to MCB. It has also been noted that, compared with case-2 of MCBs, the MCBs of case-1 have larger time duration due to the tunneling effects and intershell coupling between adjacent tubes.

6.3 Comparison between the results extracted from Case-1 and Case-2 of MCBs-based interconnects

Fig.6.5 illustrates the dependence of positive noise voltage peaks on temperature for MCB constituted in four different structures under case-1 and case-2 at the far end of victim in capacitively coupled interconnects.

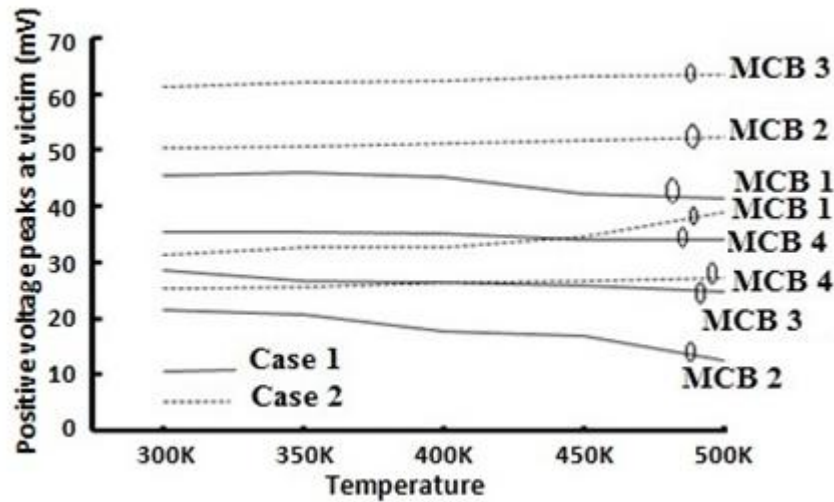


Fig.6.5. Variation of positive voltage peak of MCB constituted in four different structures under case-1 and case-2 with variation in temperature.

It is observed that, compared with MCB-1, MCB-3, MCB-4 of case-1 and other four structures constituted under case-2, the MCB-2 of case-1 has lower positive voltage peaks at any specific temperature from 300K to 500K. This is due to the dominance of the higher value of line resistance and capacitance associated with MCB-2 (case-1) over

its self inductance at any specific temperature, ranging from 300K to 500K (see Table II and III). However, the four structures of MCB constituted under case-2 have larger positive voltage peaks as compared to other corresponding MCB structures of case-1 at any specific temperature from 300K to 500K. This is due to the fact that, compared with case-1, the MCBs constituted under case-2 have smaller value of line resistance and ground capacitance. It may also be noted, the victim line of MCB-3 based capacitively coupled interconnects gets more prone to crosstalk noise.

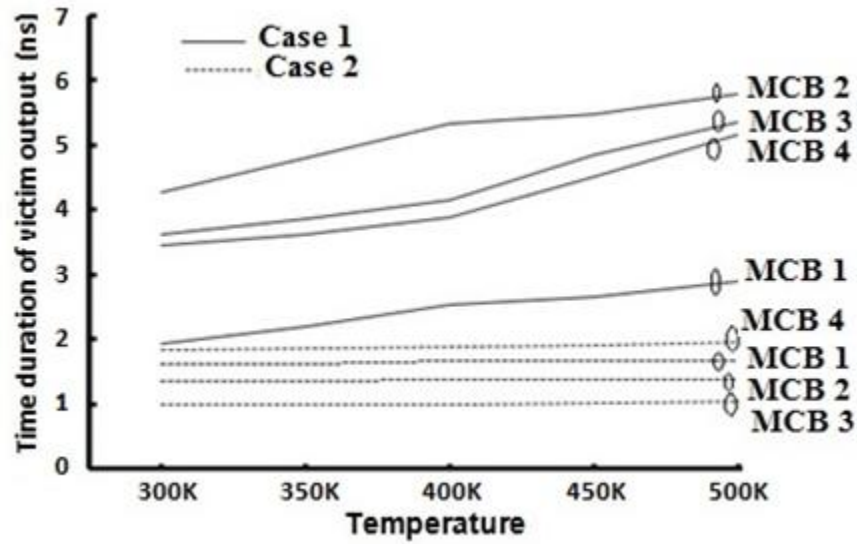


Fig.6.6. Variation of time duration of MCB constituted in four different structures under case-1 and case-2 with variation in temperature.

Fig.6.6 reveals the dependence of time duration of the victim output waveform on temperature from 300K to 500K for MCBs constituted in four different structures under case-1 and case-2. It is observed that the time duration of transient response at victim line gradually increases with rise in temperature, ranging from 300K to 500K, for both cases of MCB but this variation is observed to be more in case-1 of MCB as compared to case-2. The gradual rise of time duration indicates the dominance of line resistance over inductance and capacitance with rise in temperature. It has also been noted that, compared with other structures of MCB, the MCB-2 of case-1 have larger time duration due to the tunneling effects and intershell coupling. It may be seen from Eqs (34) and (36) that the equivalent resistance and capacitance of MCB are increased by incorporating tunneling effects and intershell coupling in the circuit parameter models.

These values of resistance and capacitance are shown in Table 4.2 for four different structures of MCB (case-1) at 300K.

6.4 Conclusion

In this section comparative performance analysis of MCB interconnect with copper interconnect is done. Positive crosstalk voltage peak in copper interconnect is more than that of MCB interconnect because of higher temperature-dependent circuit parameters associated with copper. Similarly time duration variation of transient response is observed to be more in copper as compared to MCB due to the dominance of line resistance and inductance over its capacitance with rise in temperature. From the above temperature-dependent analyses, it can be seen that the variations in crosstalk-induced voltage noise with rise in temperature are observed to be less in MCBs constituted under case-1 and case-2 as compared to copper. However, the victim line of MCB-2 gets less prone to crosstalk-induced noise voltage levels (positive voltage peaks) among other structures of MCB in case-1 with rise in temperature. Moreover, compared with all four structures of MCB under case-2, the MCBs of case-1 have lower crosstalk-induced noise voltage levels at victim far end for any specific temperature in the range 300K to 500K, due to tunneling effects and intershell coupling.

Chapter 7

Conclusion and Suggestion for Future Work

7.1 Introduction

In this chapter, the important findings are given below with following sub-sections. A realistic CNT bundle contains a mix of Single walled carbon nanotubes (SWCNTs) and Multi walled carbon nanotubes (MWCNTs). Both SWCNT and MWCNT have their own advantages. So, in MCB both these CNTs are combined and the performance is improved in comparison to SWCNTs and MWCNTs individually. So this chapter contains conclusion based on the analysis of MCB and copper interconnects. The suggestion for the future work is also given in sub-section 7.3.

7.2 Summary of Important Findings

7.2.1 Crosstalk Analysis – A Review

In this section, work done by the researchers is discussed. Both SWCNT and MWCNT perform better than copper as semi global and global interconnect. MCB based interconnect can outperform both impure SWCNT and MWCNT interconnect as well as Cu interconnect. But it does not perform better than the pure metallic densely packed SWCNT bundle. A lot of research work has been done on crosstalk effects due to coupling and solution is found to optimize the performance. But a very less work has been done on temperature dependent crosstalk analysis for SWCNT or MWCNT interconnects and no work is done for mixed CNT bundle.

7.2.2 Temperature-Dependent Circuit Modeling of Mixed CNT Bundle

The temperature dependent modeling of SWCNT bundle and MWCNT bundle is discussed and after that the combined equations for the MCB are discussed considering the coupling and tunneling effects. Temperature dependent modeling of copper based interconnects is also given. Resistance of SWCNT bundle is less than MWCNT bundle whereas value of inductance and capacitance is less for MWCNT bundle. In case of

copper interconnects, value of all the electrical parameters (resistance, inductance and capacitance) is more than CNT bundle interconnects.

7.2.3 Temperature-Dependent Impedance Analysis

The impedance of the different structures of MCB is compared with the copper based interconnects. For the temperature ranging from 300K to 500K, resistance of MCB is very less than that of copper interconnect. As temperature increases inductance decreases and capacitance seems to be constant for whole range of temperature. When compared the parameters for case-1 and case-2, the values of temperature-dependent circuit parameters using case-2 are less for four different structures of MCBs.

7.2.4 Thermally Aware Crosstalk Analysis in Coupled Mixed CNT Bundle Interconnects

The crosstalk analysis is done for copper and MCB based interconnects. With the increase in temperature crosstalk noise voltage peak shifts to the right so duration of noise increases and the peak voltage decreases for MCB based interconnects. For Cu the behavior is somewhat different as for copper both time duration and voltage peak increase with increase in temperature.

7.2.5 Comparative Analysis Between Interconnects of Mixed CNT Bundles and Copper

The comparative performance analysis of MCB interconnect with copper interconnect is done. Crosstalk voltage peak in copper interconnect is more than that of MCB interconnect because of higher temperature-dependent circuit parameters associated with copper. Similarly time duration variation of transient response is observed to be more in copper as compared to MCB due to the dominance of line resistance and inductance over its capacitance with rise in temperature. So it can be concluded that the variations in crosstalk-induced voltage noise with rise in temperature are observed to be less in MCBs constituted under case-1 and case-2 as compared to copper. However, the victim line of

MCB-2 gets less prone to crosstalk-induced noise voltage levels (positive voltage peaks) among other structures of MCB in case-1 with rise in temperature.

The effect of temperature variations on crosstalk induced noise voltage waveform, at the far end of victim line, for different structures of MCB constituted under case-1 and case-2, has been investigated. As temperature raises from 300K to 500K, compared with its copper counterpart, the crosstalk-induced voltage levels at victim far end in MCB based interconnects for both cases are found to be significantly low. The time duration of the capacitively coupled victim output waveform increases with rise in temperature for both MCB and copper interconnects, but the variation is observed to be small in MCB based interconnects, due to its small values of temperature dependent circuit parameters. Further for case-1, simulation results reveal that the MCB-2 has lower positive voltage peaks at any specific temperature from 300K to 500K; while the MCB-1 has smaller time duration of victim output. Moreover, in comparison between case-1 and case-2, as temperature of the interconnect increases, the victim line gets less prone to crosstalk-induced noise in MCB interconnects constituted under case-1, due to tunneling effects and intershell coupling. This temperature dependent analysis makes MCB interconnects an attractive and promising alternative to copper in modern VLSI design.

7.3 Suggestion for Future Work

As it is concluded from the results that performance of mixed CNT bundle is much better than copper interconnects. Further research can be done to find an optimized structure of mixed CNT bundle with best performance. Impedance and coupling of MCB both depends on structure which further affects the performance. As GNR is easy to fabricate, so the temperature-dependent comparative performance analysis of mixed CNT bundle and GNR based interconnect can be done. Main focus should be on developing better technology to fabricate CNT interconnects for the commercial purpose.

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List of Publication

S. No.	Author Name	Tiltle	Journal	Status
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