ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 5, May 2014

Evaluation and Comparison of Single-Wall Carbon Nanotubes and Copper as VLSI Interconnect

Gurleen Dhillon[1], **Karamjit Singh**[2]

Student, Electronics and Communication Engineering Department, Thapar University, Patiala, Punjab, India[1]

Assistant Professor, Electronics and Communication Eng., Department, Thapar University, Patiala, Punjab, India[2]

Abstract: The work in this paper addresses the capabilities and performance of single wall carbon nanotube (SWCNT) bundles as interconnects for applications in VLSI circuits. The carbon nanotube (CNT) bundles have potential to provide an alternate solution for the resistivity and electro-migration problems faced by traditional copper interconnect in very deep submicron technology. Using an equivalent RLC model, the performance of CNT-bundle interconnects is compared to copper wires at different lengths. It is shown in the results that carbon nanotubes can easily replace conventional Copper Interconnects. CNTs because of their superior electrical, mechanical, and thermal properties have novel applications in every day to day life applications.

Keywords: Electromigration, Grain Boundary Scattering, Interconnect, Very Large Scale Integration (VLSI)

I. INTRODUCTION

Aluminium was widely used as an interconnect material due to its good conductivity and adherence on silicon dioxide. However, with technology scaling, high current densities gives rise to considerable Electromigration. Due to certain shortcomings in aluminium, it was then realized that copper material of higher conductivity is several times more resistant to electromigration than aluminium and can with stand about five times more current density with equal reliability for IC-applications.

As technology scaling continues, problems like electromigration, surface roughness and grain boundary scattering are faced with copper as interconnect material [1, 11]. So, the next obvious choice is carbon nanotubes as interconnects due to several micro-meter long electron mean free path as compared to a few tens of nm mean free path of copper (Cu)[13].

A single wall carbon nanotube (SWCNT) is a tube-shaped hollow material, made of carbon, having a diameter measuring on the nanometre scale. The structure of CNTs is like seamless cylinders with the walls formed by one atomic layer of graphite (graphene)[27]. Beyond a certain minimum length (40nm), the performance of SWCNT-bundle interconnects is better than copper wires because of problems faced due to electromigration and grain boundary scattering. Due to high mechanical and thermal stability, high thermal conductivity and large current carrying capacity, SWCNT promises to be suitable candidate for interconnects of future VLSI circuits meeting all the requirements needed.

The rest of this paper is organised as follows: Section II presents RLC model and its impedance equations for Copper as an Interconnect; Section III presents the equivalent RLC model for Carbon Nanotube as an Interconnect and values of its impedance parameters for isolated and bundle CNTs; section IV presents the results and discussions on the R, L, C values of Copper and SWCNT and their comparison. Section V draws necessarily conclusion on the basis of results and discussion presented in this paper.

II. COPPER AS AN INTERCONNECT MATERIAL

Due to certain advantages that it offers above aluminium, copper became the preferred interconnect material, especially for submicron and deep submicron high density, high performance chips.

Cu has been seriously evaluated as an interconnect material due to its high electrical conductivity and relatively high melting temperature. Table I shows values of electrical properties like resistivity, thermal conductivity, melting point, etc. of different metals below.

TABLE I
ELECTRICAL PROPERTIES OF DIFFERENT METALS [26]

	Cu	Ag	Au	Al	W
Resistivity($n\Omega.m$)	16.78	15.91	22.14	28.24	56.50
Thermal Conductivity($Wm^{-1}k^{-1}$)	401	429	318	228	173
Melting Point(k)	1085	962	1064	660	3387
Corrosion in Air	poor	poor	excellent	good	good
Adhesion to SiO_2	poor	poor	poor	good	poor

Copper interconnect wires can conduct with about 40 percent less resistance than aluminium wires. Copper interconnects are also significantly more durable and 100 times more reliable over time, and can be shrunk to smaller sizes than aluminium; although the transition from aluminium to copper required significant developments in fabrication techniques, including radically different methods for patterning the metal as well as the introduction of barrier metal layers to isolate silicon from potentially damaging the copper atoms [18].

A. Resistance of Copper as an Interconnect

The resistance of Copper Interconnect is given by [25] equation (1) as-

$$R_{Cu} = \rho \left(\frac{l}{w.t}\right) \quad (1)$$

where, 'ρ' is the resistivity of copper and it varies with technology, 'l' is the interconnect length, 'w' is the width, 't' is thickness of the wire and are technology dependent parameters [24].

B. Capacitance of Copper as an Interconnect

The capacitance of copper as an interconnect material is given by the Ground Capacitance as shown in Fig. 1 below-

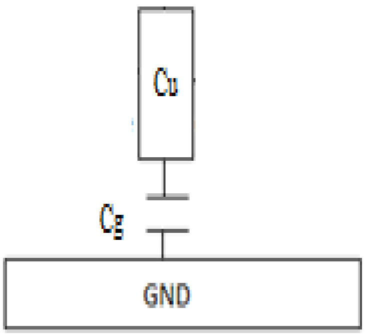

Fig. 1. Ground Capacitance in copper [25]

$$C_g = \epsilon\left[\frac{w}{h} + 2.22\left(\frac{s}{s+0.70h}\right)^{3.19} + 1.17\left(\frac{s}{s+1.51h}\right)^{0.76}\left(\frac{t}{t+4.53h}\right)^{0.12}\right] \quad (2)$$

where, 'Cg' is ground capacitance,'s' is the separation between copper wires and is taken equal to the width 'w';'ϵ' is the permittivity of copper wire and its value depends upon technology.

C. Inductance of Copper as an Interconnect

The Inductance of Copper wire as an interconnect [25] is given by-

$$L_S = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{2l}{w+t}\right) + \frac{1}{2} + 0.22\left(\frac{w+t}{l}\right)\right] \quad (3)$$

Where, u_o is permeability of copper.

III. CARBON NANOTUBES AS AN INTERCONNECT MATERIAL

Carbon nanotubes are the strongest and stiffest materials discovered in terms of tensile and thermal strength [20]. Basically, there are two types of CNTs- Single walled CNT (SWCNT) and Multiwall CNT (MWCNT) [7,12].CNTs constituted by only one thin wall of graphene sheet are SWCNTs with diameter of the order of 1-2nm. There are some CNTs which consist of a multiple of concentric SWCNT like graphene tubes. These are termed MWCNT. Among the two forms of CNTs as shown in Fig. 2, SWCNT should have been the choice because of its lower resistivity resulting from longer mean free path as an interconnect material.

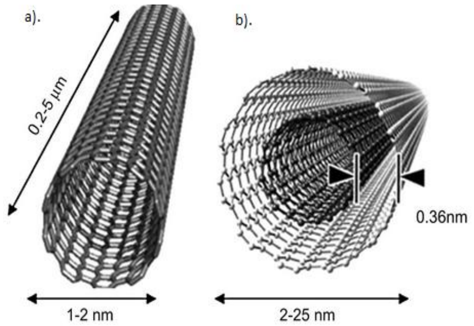

Fig.2.a). Single wall CNT (SWCNT) and b). Multi wall CNT (MWCNT)

Metallic SWCNTs are attractive interconnect materials because of their high thermal and mechanical stability, thermal conductivity as high as 5800W/mk, and have the ability to carry current in excess of 10^{14} A/m^2 current density even at temperatures higher than 200°C and Fermi velocity comparable with that of a metal of the order,$8x10^5$ m/s[17].

A. Equivalent RLC Circuit Model For an Isolated SWCNT

The development of an equivalent circuit is complete only when various impedance parameters like resistance, capacitance and inductance are taken into consideration. Assuming SWCNT to be in cylindrical form, an electrical equivalent RLC Circuit Model of the SWCNT structure is shown in Fig. 3 below-

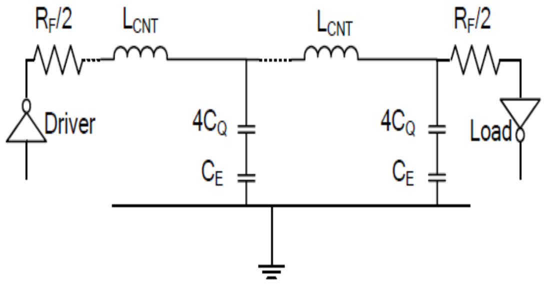

Fig.3. Equivalent RLC circuit model for an isolated SWCNT [12]

i. Resistance of SWCNT

With N conducting channels in parallel, the resistance of SWCNT is h/Ne^2T [12], where 'h' is Planks constant, 'e' is electron charge and 'T' is electron transmission coefficient. There are 4 parallel conducting channel in SWCNT (N=4). Assuming perfect contacts (T=1), the resistance of an SWCNT is $h/4e^2$. In the equivalent circuit, this resistance (R_f) is equally divided between the contacts at the two ends of the nanotube given as-

$$R_f = \frac{h}{4e^2} \quad (4)$$

If the tube length (L) is larger than mean free path then

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 5, May 2014

electron scattering gives rise to an additional resistance [5].
This resistance increases with increase in SWCNT length and is expressed as-

$$R_{CNT} = \left(\frac{h}{4e^2}\right)\frac{L}{L_0} \quad (5)$$

The contact imperfection also leads to a very large value of resistance. SWCNT resistance of the order of 6-100 kΩ has been reported [27].

i. Capacitance of SWCNT
SWCNT has two capacitances of different origins- one is Electrostatic Capacitance and the other is Quantum Capacitance. The Electrostatic capacitance (C_E) is due to charge stored by the SWCNT ground plane system as shown in Fig. 4 and is given as-

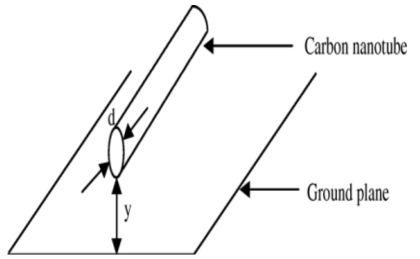

Fig.4. Equivalent Structure of Carbon nanotube placed above ground plane [27]

$$C_E = \frac{2\pi\epsilon}{ln\frac{y}{d}} \quad (6)$$

This Electrostatic Capacitance is per unit length of the nanotube. In equation (6), '∈' is permittivity of CNT, 'y' is the distance of CNT from ground plane and 'd' is the diameter of CNT.

The Quantum capacitance (C_Q) accounts for the quantum electrostatic energy stored in the nanotube when it carries current and is given by-

$$C_Q = \left(\frac{2e^2}{hv_f}\right) \quad (7)$$

Where, v_f is the Fermi velocity of the order $8x10^5$ m/sec.
As SWCNTs have four conducting channels, total effective quantum capacitance resulting from four parallel channels is $4C_Q$. When current flows, both C_E and $4C_Q$ carry same charge. Thus the two capacitances appear in series in the isolated SWCNT equivalent circuit.

i. Inductance of SWCNT
For SWCNTs, there are two types of inductances termed as- magnetic inductance and kinetic inductance. Magnetic inductance (L_M) is due to the total magnetic energy resulting from the current flowing in the wire and is expressed as-

$$L_M = \frac{\mu_0}{2}\left(\ln\frac{y}{d}\right) \quad (8)$$

The kinetic inductance (L_K) arises from kinetic energy stored in each conducting channel of the CNT.

$$L_K = \frac{h}{2e^2\,v_f} \quad (9)$$

The four parallel conducting channels in a CNT results in an effective kinetic inductance of $L_K/4$. A high resistance (7k-100k ohm) is a major disadvantage; if an isolated CNT is used as interconnect. The problem can be overcome if for interconnect application CNT bundles are used instead of isolated ones [12, 27].

B. Impedance Parameters for SWCNT Bundle Interconnect
A CNT-bundle interconnect is assumed to be composed of hexagonally packed identical metallic single-walled carbon nanotubes. Each CNT is surrounded by six immediate neighbours; their centre's uniformly separated by a distance 'x'. The densely packed structure with 'x' ='d' (CNT diameter) will lead to best interconnect performance. Out of the different types of bundles like flat, dense and sparse as shown in Fig.5; Dense CNT bundles gives the best performance [12].

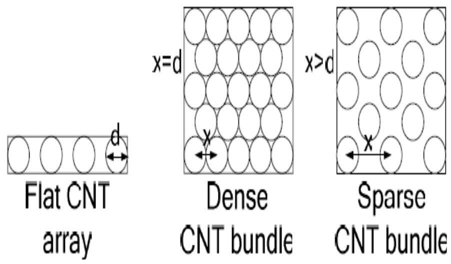

Fig.5. SWCNT Bundle as Interconnect [12]

The resistances, inductances and capacitances of a bundle can be obtained from the following expressions. The expressions to calculate the number of CNTs in the bundle are expressed below, where n_h is the number of "rows" in the interconnect bundle, n_w is the number of "columns", n_{CNT} is the total number of CNTs in the bundle-

$$n_w = \frac{(w-d)}{x}; \quad (10)$$

$$n_h = \frac{(h-d)}{\frac{\sqrt{3}}{2}x} + 1\,; \quad (11)$$

$$n_{CNT} = n_w n_h - \frac{n_h}{2}, \quad \text{if } n_h \text{ is even}$$
$$= n_w n_h - \frac{n_h - 1}{2}, \quad \text{if } n_h \text{ is odd} \quad (12)$$

The electrical equivalent RLC Circuit Model of the SWCNT bundle Interconnect is shown in Fig.6 below-

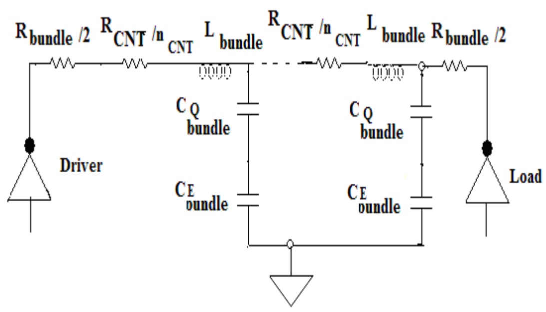

Fig.6. Equivalent RLC circuit model for an SWCNT Bundle Interconnect [21]

i. Resistance of a SWCNT-bundle
The SWCNT-bundle resistance is then given by-

$$R_{CNT(Bundle)} = \frac{\frac{h}{4e^2}\left[1+\frac{L}{L_0}\right]}{n_{CNT}} \quad (15)$$

i. Capacitance of a SWCNT-bundle

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 5, May 2014

The mutual capacitance between CNTs of the same bundle is of no consequence as it does not place any additional load on CNT interconnects. The effective capacitance (C_{Bundle}) of the series combination of quantum and electrostatic capacitance of SWCNT bundle [27] as-

$$C_{Bundle} = \left(\frac{C_{EBundle} \cdot C_{QBundle}}{C_{EBundle} + C_{QBundle}}\right) \quad (14)$$

Where, the values of $C_{EBundle}$ and $C_{QBundle}$ are given by equations (15) and (16) respectively,

$$C_{EBundle} = 2\left(\frac{2\pi\epsilon}{\ln\left(\frac{s}{d}\right)}\right) + \text{floor}\left[\left(\frac{w-d-2}{x}\right)\right]\left(\frac{2\pi\epsilon}{\ln\left(\frac{s+w}{d}\right)}\right) + \frac{3(n_h-2)(2\pi\varepsilon)}{5\ln\left(\frac{s}{d}\right)} \quad (15)$$

$$C_{QBundle} = \left(\frac{2e^2}{hv_f}\right) n_{CNT} \quad (16)$$

i. Inductance of a SWCNT-bundle

The inductance of a SWCNT bundle is given by the parallel combination of the inductances corresponding to each CNT forming the bundle, and is given by equation (17) as-

$$L_{Bundle} = \frac{L_M + L_K}{4\, n_{CNT}} \quad (17)$$

A SWCNT bundle consists of a large number of electrically parallel isolated CNTs. The result of the parallel connection is considerable reduction of resistance between the ends of the bundle. Therefore, a SWCNT bundle makes a better interconnect than the isolated counterparts [12, 27].

IV. RESULTS AND DISCUSSION

The impedance parameters of copper and SWCNT bundle Interconnect are calculated from equations (1-17). Using the values obtained from these equations, resistance, capacitance and inductance are plotted at semi global and global length at 22nm technology node for both Copper and SWCNT as shown in Fig.7-9.

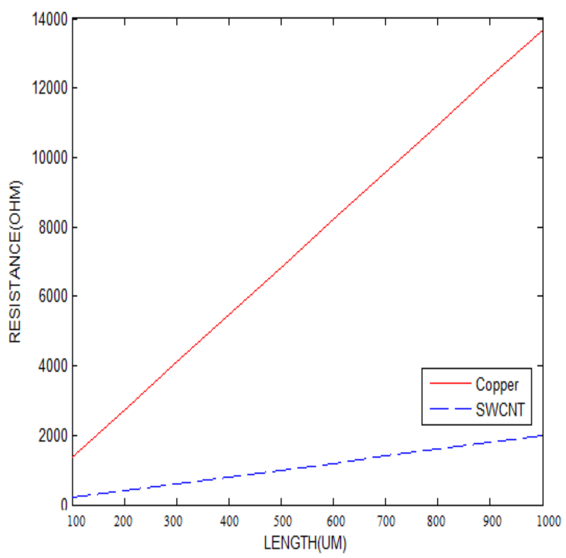

Fig.7. Comparison of Resistance between SWCNT and Copper at 22nm Technology

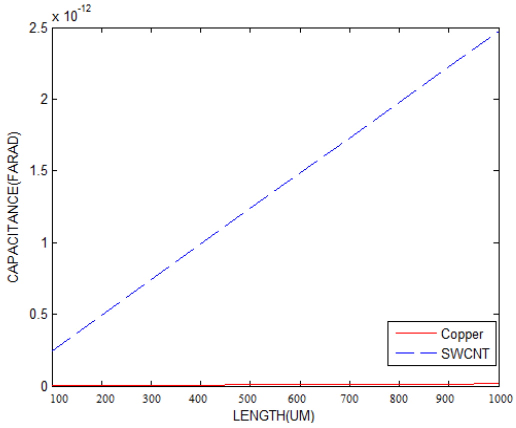

Fig.8. Comparison of Capacitance between SWCNT and Copper at 22nm Technology

It is very much evident from the results that the value of resistance and inductance is higher for copper than SWCNT at global length. This is due to shorter mean free path of electrons in case of copper as a result they undergo successive collisions at scaled technology lengths. However, the value of capacitance is more for SWCNT than copper and it contributes to more Power dissipation in this case. Further RLC delay and Power analysis is done using Tanner Tool and the simulated results are shown in Fig.10-11.

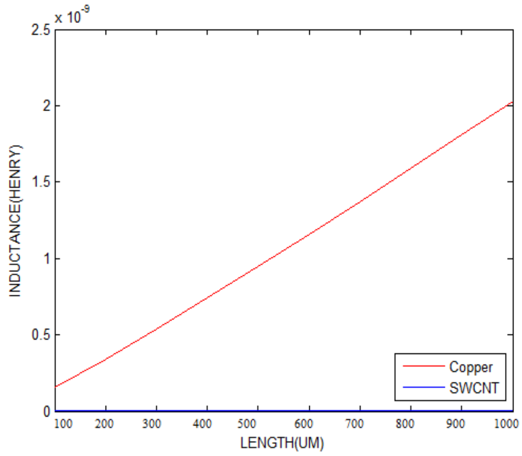

Fig.9. Comparison of Inductance between SWCNT and Copper at 22nm Technology

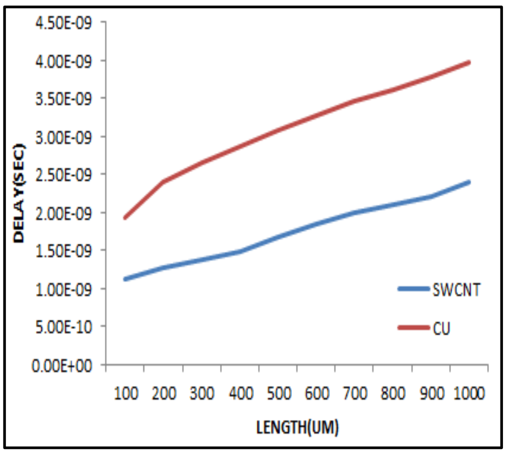

Fig.10. Delay Analysis between SWCNT and Copper at 22nm Technology

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 5, May 2014

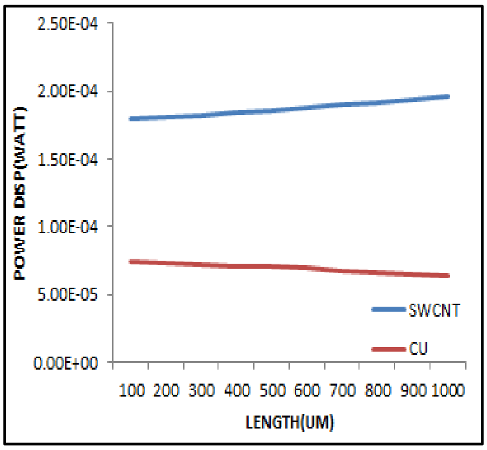

Fig.11. Power Analysis between SWCNT and Copper at 22nm Technology

Fig.10-11 shows simulation results for delay and power comparison of copper and SWCNT at 22nm technology node. Fig.10 depicts that SWCNT exhibits lesser delay than copper at all length varying from 100um to 1000um. Thus, SWCNT is advantageous in terms of speed capability than copper. Fig.11 presents that SWCNT undergo more power dissipation than copper due to its larger value of capacitance. However, this capacitance can be reduced to smaller value by varying other nanotube parameters like its diameter. By using large diameter SWCNT tube, its capacitance can be reduced to a smaller value. Thus, SWCNT proves to be a better material for interconnect applications in VLSI circuits at nanoscale technologies.

V. CONCLUSION

The comparison between copper and SWCNT as VLSI Interconnects has been studied extensively and it is found that the densely packed CNT bundle interconnects show significant improvement in performance as compared to copper interconnects, in spite of imperfect metal-nanotube contacts. The values of resistance and capacitance offered by SWCNT bundle interconnects can further affect performance parameters like delay and power dissipation. The Copper Interconnect offers a large value of resistance as compared to CNT bundle interconnects. Although the capacitance offered by SWCNT bundle is more than copper interconnect leading to more power dissipation but it can be optimized by choosing an appropriate diameter of the CNT tubes in bundle. Inductances can be ignored in the performance analysis because the resistive impedances are very much higher than the inductive impedances at any length of interconnects. Therefore, SWCNT provides an appropriate alternative to Copper Interconnects.

REFERENCES

[1] W.Steinhogl, G.Schindler, G.Steinlesberger, M.Tranving, and M.Engelhardt, “Comprehensive study of the resistivity of copper wires with lateral dimensions of 100nm and smaller,” Journal of Applied Physics, vol.97, 023706, January 2005.
[2] R. Chandel, S Sarkar and R. P. Agarwal, “Delay and Power Management of Voltage scaled Repeater Driven Long Interconnects,” Internatinal Joirnal on Modeling and Simulation, vol. 27, pp.333-339, September 2007.
[3] Amir Hosseini and Vahid Shabro, “Thermally-aware modeling and performance evaluation for single-walled carbon nanotube-based interconnects for future high performance integrated circuits,” Elsevier Science Ltd. Oxford, UK, Microelectronic Engineering, vol.87, Issue 10, pp.1955-1962, October 2010.
[4] P. L. McEuen, M. S. Fuhrer and H. Park, “Single-Walled Carbon Nanotube Electronics,” IEEE Trans. Nanotechnology, vol. 1, no. 1, pp.78-85, March 2002.
[5] Rajeevan Chandel, S. Sarkar and R.P. Agarwal “Repeater insertion in global interconnects in VLSI circuits”, Microelectronics International journal, vol.22, no.1, pp. 43–50, 2005.
[6] Dong, C., Haruehanroengra, S. and Wang, W., “Exploring Carbon Nanotubes and NiSi Nanowires as On -Chip Interconnections,” Proceedings of ISCAS, pp. 3510-3513, 2000.
[7] Dresselhaus, M.S., Dresselhaus, G. and Avouris, P., Carbon Nanotubes: Synthesis, Structure, Properties and Applications. New York: Springer- Verlag, 2001.
[8] J. Li, Q. Ye, A. Cassel, H. T. Ng, R. Stevens, J. Han and M. Meyyappan, “Bottom-up approach for carbon nanotube interconnects,” Applied Physics Letters, 82, p. 291, 2003.
[9] Gayasen, A., Vijaykrishnan, N. and Irwin, M.J., "Exploring technology alternatives for nano- scale FPGA interconnects," Proc. of DAC'05, pp. 921-926June, 2005.
[10] P. J. Burke, “Luttinger liquid theory as a model of the gigahertz electrical properties of carbon nanotubes,” IEEE Trans. Nanotechnology, vol. 1, no. 5, pp. 129–143, September 2002.
[11] Azad Naeemi, Reza Savari and James D.Meindl “Performance comparison between carbon nanotube and copper interconnects for giga scale integration (GSI),” Electron Device letters, vol. 26, No. 2, pp. 84-86, February 2005.
[12] N. Srivastava and K. Banerjee, “Performance analysis of carbon nanotube interconnects for VLSI applications,” IEEE/ACM Intl. Conference on ICCAD, vol.5, pp. 383-390, November 2005.
[13] Naushad Alam, A. K. Kureshi, Mohd. Hasan and T. Arslan, “Analysis of Carbon Nanotube Interconnects and their Comparison with Cu Interconnects,” IEEE Conference on Multimedia, Signal Processing and Communication Technologies, vol. 9, pp. 124-127, March 2009.
[14] Banerjee, K. and Srivastava, N., “Are carbon nanotubes the future of VLSI interconnections?,” 43rd ACM IEEE DAC Conference Proceedings, San Francisco, CA, pp. 809-14 2006.
[15] Mayank Kumar Rai, Nivedita and Sankar Sarkar, “Carbon Nanotube Based Interconnects for VLSI Application,” IE (I) Journal-ET, vol. 91, pp. 3-6, 2011.
[16] Hong Li, Wen-Yan Yin, Kaustav Banerjee, and Jun-Fa Mao, “Circuit Modeling and Performance Analysis of Multi-Walled Carbon Nanotube Interconnects”, IEEE Transactions on Electron Devices, Vol. 55, No. 6, June 2008.
[17] Antonio Maffucci, Giovanni Miano and Fabio Villone, “Comparison between Metallic Carbon Nanotube and Copper Future VLSI Nano-interconnects”, IEEE Workshop on Signal Propagation on Interconnects, pp.29-32, May 2007.
[18] Wu, Y. et al., “Controlled growth and structures of molecular-scale silicon nanowires,” Nano Letter 4, pp. 433– 436, 2004.
[19] F. Kreupl, et al., “Carbon Nanotubes in Interconnect Applications,” Microelectronic Engineering, 64 (2002), pp. 399- 408.
[20] B. Q. Wei, et al., “Reliability and Current Carrying Capacity of Carbon Nanotubes,” Applied Physics Letters, Vol. 79, No. 8, pp. 1172-1174, 2001.
[21] Mayank Kumar Rai, G. Spandana, Nivedita and S. Sarkar, “Power Dissipation in SWCNT-interconnect,” International Conference on Computers and Devices for Communication, 2009.
[22] M. K. Rai and S. Sarkar, “Influence of tube diameter on C nanotube interconnect delay and power output”, Physica Satus Solidi A 298, No.3, pp. 735-739, 2011.
[23] Shao-Ning Pu,Wen-Yan Yin,Senior Member,IEEE, Jun-Fa Mao,Senior Member,IEEE,and Qing H.Liu,Fellow,IEEE, “Crosstalk prediction of Single - and Double – walled Carbon-Nanotube (SWCNT/DWCNT) Bundle Interconnects”, IEEE Transactions On Electron Devices, Vol.56.No.4, pp. 560-568, APRIL 2009.
[24] International Technology Roadmap for Semiconductors, 2004, http://public.itrs.net
[25] Predictive Technology Model. [Online]. Available: www.eas.asu.edu/~ptm/.
[26] http://processmodeling.org/model_acdc/acdc.html

[27] Mayank Kumar Rai and Sankar Sarkar, "Carbon Nano Tube as VLSI Interconnect," Published in Electronic Properties Of Carbon Nanotubes, vol.1, pp 475-494, July 2011

BIOGRAPHY

Gurleen received B.Tech (Honors) degree in Electronics and Communication from Mody Institute of Technology and Science (MITS), Lakshmangarh, dist Sikar (Jaipur) in 2012. She is Pursuing Masters in Technology in VLSI Design from Thapar University, Patiala. Her research interests include Carbon Nanotubes, Digital VLSI Design, Low Power VLSI design and VLSI Interconnects.