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

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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 everyday 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 withstand 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>
<thead>
<tr>
<th>TABLE I</th>
<th>ELECTRICAL PROPERTIES OF DIFFERENT METALS [26]</th>
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<tbody>
<tr>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td>Resistivity(μΩ·m)</td>
<td>16.78</td>
</tr>
<tr>
<td>Thermal Conductivity(Wm·k⁻¹)</td>
<td>401</td>
</tr>
<tr>
<td>Melting Point(k)</td>
<td>1085</td>
</tr>
<tr>
<td>Corrosion in Air</td>
<td>poor</td>
</tr>
<tr>
<td>Adhesion to SiO₂</td>
<td>poor</td>
</tr>
</tbody>
</table>

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:

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

(1)

where, ‘\(\rho\)’ 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:

<table>
<thead>
<tr>
<th>Cg</th>
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<td>GND</td>
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$$C_g = \varepsilon \left[ \frac{w}{h} + 2.22 \left( \frac{s}{s + 0.70h} \right)^{3.19} + 1.17 \left( \frac{s}{s + 1.51t} \right)^{0.76} \left( \frac{w}{w + t} \right)^{0.12} \right]$$  

(2)

where, ‘\(C_g\)’ is ground capacitance; ‘\(s\)’ is the separation between copper wires and is taken equal to the width ‘\(w\)’; ‘\(\varepsilon\)’ 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:

$$L_g = \frac{\mu_0 l}{2\pi} \ln \left( \frac{2l}{w + t} \right) + \frac{1}{2} + 0.22(\frac{w + t}{l})$$  

(3)

Where, \(\mu_0\) 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.

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]]

\(R_e\) = \(4e^2/h\) (4)

If the tube length (\(L\)) is larger than mean free path then
electron scattering gives rise to an additional resistance [5]. This resistance increases with increase in SWCNT length and is expressed as-

\[ R_{\text{CNT}} = \left( \frac{h}{4e^2} \right) \frac{L}{L_0} \]  

(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-

\[ C_E = \frac{2\pi \varepsilon}{h y} \]  

(6)

This Electrostatic Capacitance is per unit length of the nanotube. In equation (6), \( \varepsilon \) 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-

\[ C_Q = \frac{2\pi^2}{h v_f^2} \]  

(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-

\[ L_M = \frac{\mu_0}{2} \left( \ln \frac{\Sigma}{d} \right) \]  

(8)

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

\[ L_K = \frac{h}{2e^2 v_f} \]  

(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 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].

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-

\[ n_w = \frac{(n_h-d)}{x} + 1 ; \]  

(10)

\[ n_h = \frac{h-0}{d} ; \]  

if \( n_h \) is even

\[ n_{CNT} = n_w n_h - \frac{n_h}{2} , \]  

if \( n_h \) is odd

(12)

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

i. Resistance of a SWCNT-bundle

The SWCNT-bundle resistance is then given by-

\[ R_{\text{CNT(Bundle)}} = \frac{h}{2\pi^2 v_f} \left( 1 + \frac{1}{n_{CNT}} \right) \]  

(15)

i. Capacitance of a SWCNT-bundle
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 ($C_{\text{Bundle}}$) of the series combination of quantum and electrostatic capacitance of SWCNT bundle [27] as-

$$C_{\text{Bundle}} = \left( C_{\text{EBundle}} + C_{\text{QBundle}} \right)$$  \hspace{1cm} (14)

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

$$C_{\text{EBundle}} = 2 \left( \frac{2\pi \varepsilon}{\ln \left( \frac{d}{s} \right)} \right) + \frac{3(n_b - 2)(2\pi\varepsilon)}{5 \ln \left( \frac{d}{s} \right)}$$ \hspace{1cm} (15)

$$C_{\text{QBundle}} = \left( \frac{2\pi e^2}{h v_f} \right) n_{\text{CNT}}$$ \hspace{1cm} (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-

$$L_{\text{Bundle}} = \frac{L_{\text{Ma}} + L_{\text{K}}}{4 n_{\text{CNT}}}$$ \hspace{1cm} (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](image)

**Fig.7. Comparison of Resistance 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.8. Comparison of Capacitance between SWCNT and Copper at 22nm Technology](image)

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

![Fig.9. Comparison of Inductance between SWCNT and Copper at 22nm Technology](image)

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

![Fig.10. Delay Analysis between SWCNT and Copper at 22nm Technology](image)

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


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.