Performance Analysis of Squarely Packed Polymorphic SWCNT Interconnect

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Abstract— **In this paper, we propose a new configuration, named squarely packed bundle of polymorphic SWCNTs, to acquire a better performance than previously developed configuration namely hexagonally packed bundle. Subsequently, we alter the existing RLC model according to the physics based requisites of our proposed configuration. We, in the end, demonstrate a comparison among extracted RLC value and delay model of Cu and differently configured SWCNT interconnects in regards to pre-defined parameters. Having analyzed our proposed squarely packed polymorphic configuration of isolated SWCNT in SWCNT-bundle, we yield a better performance of SWCNT. In fact, using this configuration, it is depicted through simulation that SWCNT bundle can outperform copper interconnect for local level interconnect. This work reinforces further the acceptability of SWCNT as interconnect to deal with scaling issue in VLSI technologies.**

Keywords— Analytical delay model; Copper interconnect; RLC model; Single wall carbon nanotube; Squarely packed bundle of polymorphic SWCNTs

I. INTRODUCTION

As the current era is going beyond Moore's law with regard to number of transistors, technology scaling is becoming a critical issue. To cope with this challenge, on-chip interconnect has been addressed as one of the most momentous catalysts to improve the performance and reliability of VLSI design [1]. To get the full essence of technology scaling, having reliable interconnect parameters i.e. Resistance, Capacitance and Inductance and interconnect metric i.e. delay models are very important.

Copper is facing hindrance to outperform in regard to interconnect delay due to the rapid growth of parasitic resistance, engendered by the mutual impact of intense grain boundary scattering, surface scattering and the existence of highly resistive diffusion barrier layer [2]. Upcoming demand for technology scaling along with increasing current density and decreasing thermal conductivity of low-K dielectrics make Cu vulnerable to electromigration (EM) at high current densities ($>1\times10^6$A/cm^2) [3,4]. Because of inducing Joule heating, substantial temperature rising behavior of metal increases the temperature of Cu due to its resistivity and decreases the maximum current carrying capacity by deteriorating the interconnect electromigration lifetime [3,5].

The advent of carbon nanotube (CNT) as interconnect makes the researchers build up RLC model and delay model to analyze the performance of integrated circuits. In fact, CNT has seized great attention due to its sublime conductivity performance. Carbon nanotubes are sheets of graphite, made of carbon atoms arranged in a honeycomb lattice, rolled into cylinders diameter varying from 0.4nm to about 3nm [6]. The two main types of CNTs are Single-walled carbon nanotubes (SWCNTs), made by rolling up a single layer of graphene sheet into a tube with a diameter of few nanometers, and multi-walled carbon nanotubes (MWCNTs), composed of rolled graphene sheet in multiple layers around itself. Though MWCNTs are metallic in nature, SWCNTs are special because of some of its unique electronic properties. Mean free path of SWCNT is more than 1μm at room temperature and the maximum current density is more than 10^6Am^{-2} with the thermal conductivity of 5.8×10^6WK^{-1} [3]. The band gap energy and electronic structure i.e. semiconducting or metallic of SWCNT depend on chirality, determined by basis vectors of the graphene lattice.

Contribution of this work:

The main contribution of this work is to propose a new configuration, called squarely packed polymorphic SWCNT bundle, for organizing SWCNTs in the bundle to achieve a better performance in terms of RLC delay. Here, we attempted to assure an optimized use of available space as most of the heretofore pursued works, illustrated in [3, 7, 8, 9, 11], in this field have used the same hexagonally packed configuration. To justify our configuration as a better one, we have used the RLC models from [2, 8, 9, 11, 13] for calculation purpose to address the challenge of size shrinkage. Eventually, having calculated delay, we came across an efficient model of squarely packed polymorphic configuration to enrich the performance of SWCNT for local level interconnects.

The rest of the paper is compiled in the following manner. A background of calculating RLC model and delay model for Cu and SWCNT interconnects are delivered in Section II. In addition, in section II, equivalent circuit parameters for Cu, isolated SWCNT and bundle SWCNT are accumulated from previous research work with some suggested improvement. Moreover, analytical delay model from Kahng's [8] work is retrieved to show a comparison among previous works and our approach. To justify this work, simulation results and discussions are presented in section III by elucidating the comparison between Cu and SWCNT bundle for every components and models. Finally, Section IV concludes the paper with our future initiatives.

II. BACKGROUND AND PREVIOUS WORKS

Consequence of the first initiative, illustrated in [11], to evaluate the performance of SWCNT interconnects and compare with copper wires leads to the direction to CNT technology development to assure interconnect advancement [11]. However, A. Raychowdhury and K. Roy have previously taken an approach in [12] to model carbon nanotubes and conduct comparative study with Cu interconnects for scaled technologies. They haven't shown

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TABLE I. RLC MODELS FOR CU AND SWCNT INTERCONNECTS

Interconnect Materials	**Interconnect Parameters Models**		
	Resistance	***Capacitance***	***Inductance***
Cu	$\rho_{size} = \frac{\rho_0}{1-\frac{3}{2k}(1-p\int_1^{\infty}\left(\frac{1}{t^3}-\frac{1}{t^5}\right)\frac{1-e^{-kt}}{1-pe^{-kt}})dt}$ $\rho_{grain} = \frac{\rho_0}{3\left\{\frac{1}{3}-\frac{1}{2}\alpha+\alpha^2-\alpha^3\ln\left(1+\frac{1}{\alpha}\right)\right\}}$ $\alpha = \frac{\lambda_{cu}}{d_g}\frac{R'}{1-R'}$ Resistivity, $\rho = \rho_{size} + \rho_{grain}$ Resistance, $R = \frac{\rho l}{w_{Cu}h_{Cu}}$	$C_C = \frac{\varepsilon h_{cu}}{d - w_{cu}}$	$L_{self} = \frac{\mu_0 l}{2\pi}\left[ln\left(\frac{2l}{w+t}\right)+\frac{1}{2}+0.2235\left(\frac{w+t}{l}\right)\right]$ $M = \frac{\mu_0 l}{2\pi}\left[ln\left(\frac{2l}{d}\right)-1+\frac{d}{l}\right]$ $L = L_{self} + M$
Isolated SWCNT	$R_{CNT} = \begin{cases}\frac{\hbar}{4e^2} \approx 6.45k\Omega; l < \lambda_{CNT} \\ \left(\frac{\hbar}{4e^2}\right)\frac{L}{\lambda_{CNT}}; l > \lambda_{CNT}\end{cases}$	$C_Q = \frac{2e^2}{hv_F}$ $C_{En} = \frac{2\pi\varepsilon}{ln\left(\frac{w}{d}\right)}$; $C_{Ef} = \frac{2\pi\varepsilon}{ln\left(\frac{2w}{d}\right)}$	$L_{kinetic} = \frac{\hbar}{2e^2v_f}$ $L_{magnetic} = \frac{\mu}{2\pi}ln\left(\frac{h}{d}\right)$ **Our case**[b]: $L_{Magnetic}{}^{large} = \frac{\mu}{2\pi}ln\left(\frac{h}{d}\right)$ $L_{Magnetic}{}^{small} = \frac{\mu}{2\pi}ln\left(\frac{h}{d_s}\right)$
Bundle SWCNT	**Conventional Case**[a]: $R_{bundle} = \frac{R_F + R_{CNT}}{n_{CNT}}$	**Conventional Case**[a]: $C_{Q_{bundle}} = C_{Q_{CNT}}.n_{CNT}$ $C_{E_{bundle}} = 2C_{En} + \frac{(n_w-2)}{2}C_{Ef} + \frac{3(n_H-2)}{5}C_{En}$ $C_{bundle} = \left(\frac{1}{C_{Q_{bundle}}}+\frac{1}{C_{E_{bundle}}}\right)^{-1}$	**Conventional Case**[a]: $L_{bundle} = \begin{cases}\frac{\frac{L_{kinetic}}{4}+L_{magnetic}}{n_{CNT}}; l < \lambda_{CNT} \\ \frac{L_{magnetic}}{n_{CNT}}; l > \lambda_{CNT}\end{cases}$
	Our case[b]: $R_{bundle}{}' = \frac{R_F + R_{CNT}}{n_{CNT}{}'}$	**Our case**[b]: $C_{Q_{bundle}}{}' = C_{Q_{CNT}}.n_{CNT}{}'$ $C_{E_{bundle}}{}' = 2C_{En} + \frac{(n_c-2)}{2}C_{Ef} + \frac{3(n_r-2)}{5}C_{En}$ $C_{bundle} = \left(\frac{1}{C_{Q_{bundle}}{}'}+\frac{1}{C_{E_{bundle}}{}'}\right)^{-1}$	**Our case**[b]: $L_{bundle} = \begin{cases}\frac{L_{kinetic}}{4n_{CNT}{}'}+\left(\frac{n_{CNT}{}^{large}}{L_{Magnetic}{}^{large}}+\frac{n_{CNT}{}^{small}}{L_{Magnetic}{}^{small}}\right)^{-1}; l < \lambda_{CNT} \\ \left(\frac{n_{CNT}{}^{large}}{L_{Magnetic}{}^{large}}+\frac{n_{CNT}{}^{small}}{L_{Magnetic}{}^{small}}\right)^{-1}; l > \lambda_{CNT}\end{cases}$

[a] **Conventional case:** Number of columns in CNT bundle, $n_c = \text{floor}\left\langle\frac{w-d}{x}\right\rangle$; Number of rows in CNT bundle, $n_r = \text{floor}\left\langle\frac{2(h-d)}{\sqrt{3}x}\right\rangle + 1$;
Here, floor (A) indicates the nearest integers less than or equal to A. Total number of CNTs, $n_{CNT} = \begin{cases} n_c n_r - \frac{n_r}{2}, \text{if } n_r \text{ is even} \\ n_c n_r - \frac{n_r-1}{2}, \text{if } n_r \text{ is odd}\end{cases}$

[b] **Our case:** Number of columns in CNT bundle (larger), $n_c = \text{floor}\left\langle\frac{w-d}{x}\right\rangle$; $n_c' = n_c - 1$ (smaller CNTs); Number of rows in CNT bundle (larger), $n_r = \text{floor}\left\langle\frac{h-d}{x}\right\rangle$; $n_r' = n_r - 1$(smaller CNTs);
Number of larger CNTs, $n_{CNT}{}^{large} = n_c n_r$; Number of smaller CNTs, $n_{CNT}{}^{small} = n_c' n_r'$; Total number of CNTs, $n_{CNT}' = n_c n_r + n_c' n_r'$

any calculation for geometry of SWCNT bundle to analyze near field and far field electrostatic capacitance and mutual inductance. In fact, A. Raychowdhury and K. Roy have used a resistance model for Cu interconnect including grain boundary scattering and size dependent component and coupling capacitance model between adjacent copper wires in [4,12].

Subsequently, some very noticeable works on developing RLC model for SWCNT have been done by [2, 4, 13]. A transmission line model has been suggested in [13] by considering the fundamental contact resistance and scattering resistance as lump and distributed respectively. It has been concluded by researcher Hong li [13] that CNT performs better than Cu interconnect only at intermediate and global interconnect level. In [2,3], N. Srivastava and K. Banerjee have used hexagonally packed uniform SWCNTs composition to estimate the electrostatic along with quantum capacitance and inductance of SWCNT bundle.

Ullah and Chowdhury [14-15] developed the model, comprised the impacts of driver resistance and load capacitance, to obtain a delay of distributed RLC network

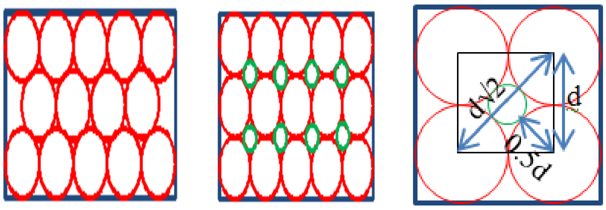

Fig. 1 (a) hexagonally packed uniform SWCNTs composition (b) squarely packed polymorphic SWCNTs composition (c) Geometry to determine the diameter of smaller SWCNTs using second-order approximation for individual real pole and complex pole. Ullah and Chowdhury [16] bettered their previous work [14-15] by suggesting analytical delay models of high speed RLC interconnect for three different scenarios (i.e. complex, real, and double pole) using second order approximation. They demonstrated the more delay characteristics of complex pole-based model over the real pole-based model.

A. *Modeling of Cu interconnect*

For the purpose of comparison, we have used following RLC models, mentioned in Table I, of Cu interconnect and simulated for synthesis and analysis.

1) Resistance: As shown in Table I, k_1 is the ration of grain diameter (d_g) that assume to be equal to width of the copper wire (w_{cu}), and the electron mean free path (λ_{cu}) is 40nm for copper at room temperature, where k_2 is the ration of film thickness (h_{cu}). Finally, we can obtain k using the following mathematical expression in (1).

$$k = \frac{k_1 k_2}{|k_1 - k_2|} \tag{1}$$

In the copper resistance equation, ρ_0 $(1.9\times10^{-8}\Omega m)$ is resistivity of the bulk material, $R'=0.5$ $(0 \le R' \le 1)$ is the grain boundary reflection coefficient, fraction of electrons that are not scattered by the potential barrier at a grain boundary, $p=0.6$ is the fraction of electrons scattered specularly at the surface [2].

2) Capacitance: Modeling of coupling capacitance (C_c) has been excerpted from [4] and shown in Table 1.

3) Inductance: A fast and accurate 3D geometry model has been developed in [17] to calculate self-inductances of wires and their mutual inductances of the cascade segments.

B. *Modeling of SWCNT-bundle interconnect*

For the purpose of comparison, we have used following RLC model, mentioned in Table I, of SWCNT-bundle and simulated for synthesis and analysis.

In our proposed configuration, the diameter of the green colored smaller CNTs, depicted in Figure 1, can be calculated using the following mathematical model of (2).

$$d_s = d\sqrt{2} - d \cong 0.414d \tag{2}$$

1) Resitance: As mentioned in [2, 3], the total resistance of a CNT is the accumulation of resistance evolve of three facts such as the fundamental 1D system contact resistance, scattering resistance and the imperfect metal-nanotube contact resistance. The fundamental resistance can be defined as $R_F = \hbar/4e^2$, where plank constant, $\hbar = 6.63\times10^{-34}\text{kgm}^2\text{s}^{-1}$ and electron charge, $e = 1.602\times10^{-19}$coulombs.

TABLE II. RLC DELAY MODELS

Reference	**Name of the Model**	**Delay Models**
Kahng's model [10]	Real Poles[c, d]	$\tau_r = 2.36.\frac{2b_2}{b_1 - \sqrt{{b_1}^2 - 4b_2}}$
	Complex Poles[c, d]	$\tau_c = 1.66.\frac{2b_2}{b_1 - \sqrt{4b_2 - {b_1}^2}}$
	Double Poles[c, e]	$\tau_d = \frac{2b_2}{b_1} ln\left(10\left(1 + \frac{2T_{0.9}}{b_1}\right)\right)$

[c] $b_1 = R_sC + R_sC_T + \frac{RC}{2} + RC_T$

[d] $b_2 = \frac{R_sRC^2}{6} + \frac{R_sRCC_T}{6} + \frac{(RC)^2}{24} + \frac{R^2CC_T}{6} + L_sC + L_sC_T + \frac{LC}{2} + LC_T$

[e] $T_{0.9} = 1.02RC + 2.3(R_s(C + C_T) + RC_T)$

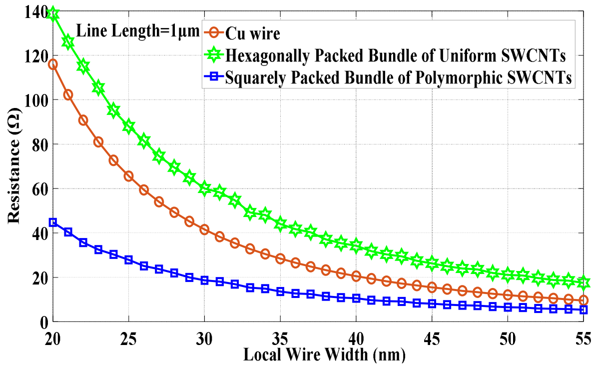

Fig. 2 Resistance of 1μm long local interconnect of Cu, uniform and squarely polymorphic SWCNT bundle.

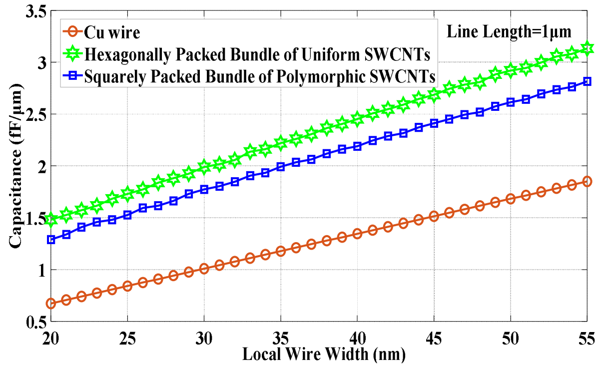

Fig. 3 Capacitance of 1μm long local interconnect of Cu, uniform and squarely polymorphic SWCNT bundle.

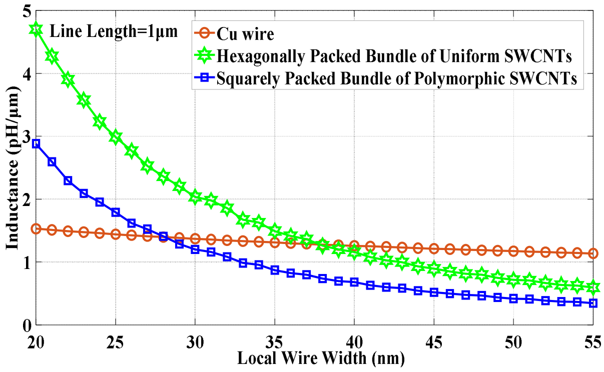

Fig. 4 Inductance of local interconnect for Cu, uniform and squarely polymorphic SWCNT bundle.

2) Capacitance: According to [2, 9], two sources of CNT capacitance are electrostatic capacitance (C_E), obtained by placing SWCNT presumably a thin wire with a diameter 'd' and distance 'y' away from ground, and quantum capacitance (C_Q), estimated for the quantum electrostatic energy stored in the nanotube during carrying current. We are going to hold the assumption of [2] that the contribution of CNTs are entirely surrounded as a green colored CNTs (shown in Figure 1(b)) since we know from [2] that CNTs entirely enclosed by other nanotubes have negligible electrostatic coupling capacitance to ground compared to those along the edges of the bundle. Hence, we have taken into account the

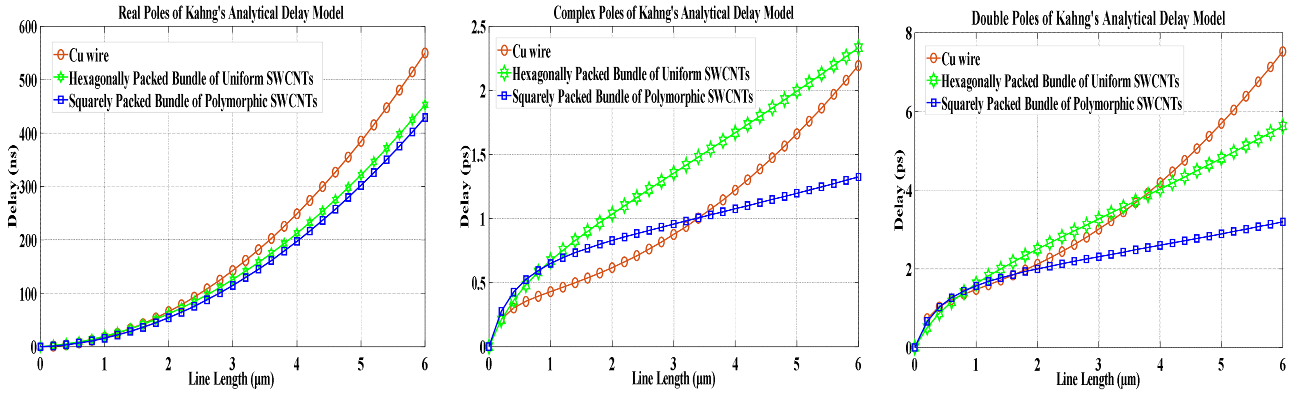

Fig. 5 Simulation resuls of Kahng's delay models of Cu, uniform and squarely polymorphic SWCNT bundle.

contribution of only all of the encompassing SWCNTs, depicted by red color in Figure 1(b), to estimate the electrostatic capacitance, mentioned in Table I.

3) Inductance: The overall inductance, shown in Table 1, of SWCNT bundle can be calculated by taking the parallel combination of all of the individual CNTs, responsible to create SWCNT bundle [2]. The two components of the inductance of an isolated SWCNT are magnetic inductance $(L_{magnetic})$, obtained by estimating the magnetic field induced by the current carried by the isolated SWCNT wire *'y'* distance away from a ground plane, and kinetic inductance $(L_{kinetic})$. We have followed the footstep of [2] to reckon the kinetic inductance by considering its existence only for $L < \lambda_{CNT}$ which means there is no need for potential energy to move an electron to conduct. A potential drop does, otherwise, $(L \gg \lambda_{CNT})$ exist along the nanotube length which may cause substantial error in delay calculation if kinetic inductance is included.

C. RLC Delay Model

A computationally easy, faster and more accurate analytical delay model, developed in [8] and imported in Table 2, is based on both first and second moments of the interconnect transfer function. The main reason behind to select the Kahng's model is to take the effect of inductance into account.

III. SIMULATION RESULTS AND DISCUSSION

As we are trying to figure out the RLC attributes of our newly configured SWCNT bundle for local interconnect, we simulate and extract the value of resistance, capacitance and inductance with the change of wire width by keeping the interconnect length (1μm) below the electron mean free path (1.2μm) in case of SWCNT bundle. We have taken CNTs of 1nm diameter, depicted in Figure 1 with red colored circle, and considered the distance (x) between the centers of two adjacent CNTs of 1nm.

We can remark from Figure 2 that the resistance of our configuration is lowest among all while the resistance of hexagonally packed uniform SWCNTs is the highest one and obviously higher than the Cu wire. However, In case of capacitance, shown in Figure 3, squarely packed bundle of polymorphic SWCNTs shows significant improvement compare to hexagonally packed bundle of uniform SWCNTs although it is higher than Cu wire. Besides, from Figure 4, the bundle of SWCNTs delivers more inductance than Cu wire below the 27 nm technology. It is quite obvious that our proposed configuration, the squarely packed bundle of polymorphic SWCNTs, is showing superior overall performance over Cu wire and hexagonally packed uniform SWCNTs bundle. We will justify our position further by explaining the delay model that is shown in Figure 5.

In Figure 5, we can lucidly figure out their superiority by observing the propagation delay characteristics for individual RLC interconnect model. Here we estimate the delay using Kahng's model for all three different (real poles, complex poles and double poles) scenarios [8]. Though we cannot fully determine the features of interconnects by only observing its individual RLC extraction, we can reach a decision after observing the delay behavior. Hence, in Figure 5, real pole model shows that our proposed configuration of bundle SWCNTs offers the lowest delay with respect to local interconnect line length. In fact, it shows substantially lower delay from complex poles and double poles beyond 3 μm and 2 μm respectively. Consequently, we can claim the superordinate suitability of our proposed squarely packed bundle of polymorphic SWCNT configuration to meet the future demand of high speed VLSI interconnect technology in the nanoscale domain.

IV. CONCLUSION

Throughout this paper, we tried to reexamine the previously developed model for SWCNT bundle as we realized that we could illustrate performance betterment by designing new configuration with size shrinkage. We have already validated our claim by depicting the comparison among the performance of Cu, conventional configuration and our proposed configuration with regard to delay. Based on our observation, we will dig into the performance of MWCNT and SWCNT-MWCNT composite interconnect further using our proposed configuration and also come across some improvement in the previously developed model.

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