

Performance Comparison Between Carbon Nanotube and Copper Interconnects for Gigascale Integration (GSI)

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Abstract—Physical models are used to determine the ultimate potential performance of carbon nanotube interconnects and compare them with minimum-size copper wires implemented at various technology generations. Results offer important guidance regarding the nature of carbon nanotube technology development needed for improving interconnect performance. Since wave propagation is slow in a single nanotube, nanotube bundles with larger wave speeds must be used. At the 45-nm node (year 2010), the performance enhancement that can be achieved by using nanotube bundles is negligible, and at the 22-nm node (year 2016) it can be as large as 80%.

Index Terms—Interconnections, kinetic inductance, modeling, molecular electronics, quantum wires.

I. INTRODUCTION

AS interconnect feature sizes shrink, copper resistivity increases due to surface and grain boundary scatterings and also surface roughness [1]. Furthermore, wires, especially power and ground lines, are becoming more and more vulnerable to electromigration because of rapid increases in current densities [2]. In contrast, carbon nanotubes exhibit a ballistic flow of electrons with electron mean-free paths of several micrometers, and are capable of conducting very large current densities [3]. Carbon nanotubes are therefore proposed as potential candidates for signal and power interconnection [4], [5]. In this letter, after reviewing the circuit models for single-wall carbon nanotubes (SWCN), the performances of copper wires and nanotube interconnects are compared. The results offer important guidance regarding the nature of carbon nanotube technology development needed for improving interconnect performance.

II. CIRCUIT MODELS FOR METALLIC CARBON NANOTUBES

Neglecting electron spin and sublattice degeneracy, the dc conductance of an ideal (ballistic) quantum wire is independent of length and is equal to e^2/h , where h is the Plank constant, and e is electron charge [6]. The current carriers of a nanotube occupy the one-dimensional conduction bands with very low density of states, and hence the kinetic energy stored in current is

so large that it results in a very large kinetic inductance per unit length [6]–[8]

$$l_k = \frac{h}{(2e^2v_F)} \quad (1)$$

where v_F is the Fermi velocity [8]. For graphene and hence carbon nanotubes $v_F = 8 \times 10^5$ m/s [6], [7]. The kinetic inductance per unit length of carbon nanotubes is therefore around 16 nH/ μ m, more than four orders of magnitude larger than its magnetic counterpart.

To add electric charge to a quantum wire, one must add electrons to available states above the Fermi level (Pauli exclusion principle); hence, there is a quantum capacitance of

$$c_Q = \frac{2e^2}{(hv_F)} \quad (2)$$

in series with the electrostatic capacitance [6]–[8]. The quantum capacitance of a carbon nanotube is 100 aF/ μ m, and is of the same order of magnitude as its electrostatic counterpart.

Electron spin and sublattice degeneracy result in four parallel channels through which three spinmodes and one chargemode can travel [6]. The wave propagation speed for the charge mode is

$$v = \sqrt{\frac{4}{l_K} \left(\frac{1}{c_E} + \frac{1}{4c_Q} \right)}. \quad (3)$$

Assuming that the electrostatic and quantum capacitances are equal, the wave speed is $\sqrt{5}v_F = 1.78 \times 10^6$ m/s, which is 162 times smaller than the speed of light in free space. The speed of spin-modes through which no charge is transferred is always v_F regardless of nanotube electrostatic capacitance [6].

III. IDEAL CARBON NANOTUBES VERSUS COPPER WIRES

For the 22-nm node (year 2016), latencies of ideal carbon nanotube and copper interconnects are plotted versus length in Fig. 1. For copper interconnects, the distributed RC model is used [9], and copper resistivity has been calculated by the combination of Fuchs–Sondheimer and Mayadas–Shatzkes models for surface scattering and grain boundary scattering [1], [10], respectively.

Due to large values of contact resistance and characteristic impedance of a single nanotube, many of them need to be used in parallel for interconnect applications. Compared to a single nanotube, a monolayer of nanotubes in parallel above a ground plane as shown in Fig. 1 has a smaller inductance. However, it has a larger capacitance. Hence, by connecting more and more

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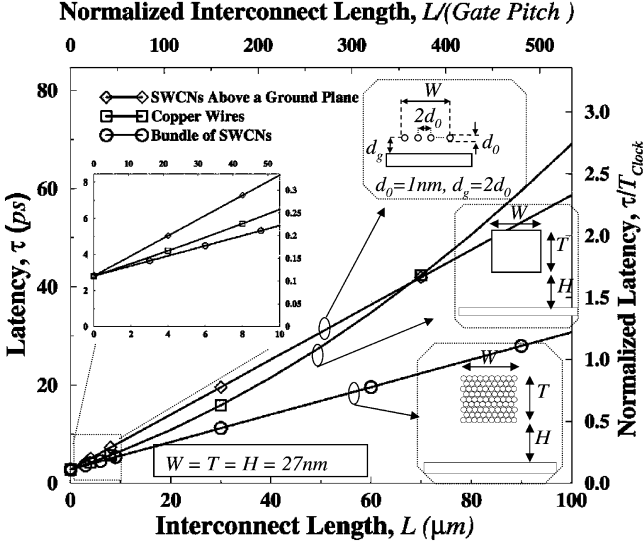


Fig. 1. Latency versus interconnect length for ideal single-layered carbon nanotubes above a ground plane, minimum-sized copper wires implemented at the 22-nm technology node (year 2016) and bundles of ideal SWCNs for $n > 100$. For copper interconnects, surface scattering co-efficient, p , and grain boundary reflection coefficient, R , are pessimistically assumed to be 0 and 0.5, respectively. Mean-free path of electrons in ideal carbon nanotubes is larger than their length.

nanotubes in parallel, the wave propagation speed does not improve significantly. Latency of such a “single layer” nanotube interconnect is therefore

$$\tau_{\text{nano}} = 0.7R_{\text{tr}}C_L + \frac{L}{(\sqrt{5}v_F)} \quad (4)$$

where R_{tr} is driver resistance (equal to the line characteristic impedance for impedance matching), C_L is load capacitance, and L is interconnect length.

In contrast, a bundle of closely packed parallel carbon nanotubes above a ground plane as shown in Fig. 1 has a capacitance per unit length approximately equal to that of a single nanotube. If all cross-sectional dimensions scale proportionally with increasing the number of nanotubes within the bundle, n , the overall capacitance per unit length remains constant (independent of n). The kinetic inductance per unit length, however, decreases linearly with n , because of which the wave propagation speed increases by \sqrt{n} as (3) shows. At the contacts, good connections to all nanotubes within the bundle are needed such that all nanotubes can contribute to conduction. The distance between nanotubes within the bundle is desired to be as small as possible to have the largest nanotube density. It has been optimistically assumed that there is no unwanted quantum coupling between nanotubes within the bundle. Further investigation is needed to verify this assumption even though preliminary measurements and analyzes indicate that the coupling between nanotubes within a bundle is weak [11], [12].

For $n > 100$, the wave travel time becomes much smaller than the RC charge up time of most typical interconnects even at the end of the International Technology Roadmap for Semiconductors, hence, latency would be equal to

$$\tau_{\text{bundle}} = 0.7R_{\text{tr}}(c_{\text{bundle}}L + C_L) \quad (5)$$

where c_{bundle} is capacitance per unit length of the bundle of nanotubes. Since the diameter of SWCNs can be less than 1 nm

[13], a bundle of, for instance, 400 SWCNs can be as narrow as 20 nm.

IV. NONIDEAL CARBON NANOTUBES VERSUS COPPER WIRES

Even initially ideal carbon nanotubes become disordered once they are physisorbed on a surface [3]. Electron mean-free path, L_0 , in real carbon nanotubes is, hence, finite and their resistance increases with length. There are inconsistent results published in literature, both experimental and theoretical, regarding the dependency of resistance on length; some indicating an exponential relationship ($R = R_0 \exp(L/2L_0)$) [14], [15], and some showing a linear dependency ($R = R_0(1 + L/L_0)$) [16], [17], where R_0 is the resistance of a bundle of ballistic nanotubes (ideally equal to $h/(4e^2n)$). In this section, these two possible dependencies are considered separately.

$$\text{Exponential Dependency } \left(R = R_0 e^{\frac{L}{2L_0}} \right).$$

In the inset in Fig. 2, latencies of SWNT bundles and copper interconnects implemented at the 22-nm node are plotted versus interconnect length for $L_0 = 5 \mu\text{m}$ and $L_0 = 10 \mu\text{m}$. There is a length beyond which latency of SWNT bundles becomes larger than that of copper wires. As a rule of thumb, this critical length is roughly ten times the electron mean-free path in SWCNs. The performance enhancement that can be achieved by using nanotube bundles is a function of interconnect length, and its maximum is

$$\frac{\tau_{\text{copper}} - \tau_{\text{Bundle}}}{\tau_{\text{Bundle}}} \Big|_{\text{max}} \approx \max \left\{ \left[0.76 \frac{L_0 r_{\text{int}}}{R_{\text{tr}}} \left(\ln \frac{2R_{\text{tr}}}{R_0} - 1 \right) - 0.24 \right], 0 \right\} \quad (6)$$

which is plotted in Fig. 2 versus electron mean-free path for four various technology generations. It can be seen that the performance enhancement at the 45-nm node (year 2010) is negligible even if mean-free paths as large as 10 or 20 μm are achieved. This is mainly due to small resistance per unit length of copper wires. At the 22-nm node (year 2016), however, nanotube bundles are 30% faster for mean-free path of 5 μm , and they can be 80% faster if achieving a mean-free path of 10 μm is feasible. Theoretical calculations show that electron mean-free path in SWCNs can be as large 10 μm [3].

$$\text{Linear Dependency } \left(R = R_0 \left(1 + \frac{L}{L_0} \right) \right).$$

In the inset in Fig. 3, latencies of SWNT-bundles and copper interconnects implemented at the 22-nm node are plotted versus interconnect length for $L_0 = 0.1 \mu\text{m}$, 1 μm and 10 μm assuming that nanotube resistance increases linearly with length. It can be seen that nanotube bundles outperform copper wires unless they have very short mean-free paths ($\sim 0.1 \mu\text{m}$). The speed improvement that can be attained by using nanotube bundles is

$$\frac{\tau_{\text{copper}} - \tau_{\text{Bundle}}}{\tau_{\text{Bundle}}} \approx \frac{R_{\text{tr}} + 0.5r_{\text{int}}L}{R_{\text{tr}} + \frac{0.5R_0L}{L_0}} - 1 \quad (7)$$

and it increases as interconnect length increases. This performance gain is plotted versus mean-free path in Fig. 3 for 100- μm -long interconnects implemented at four various technology generations. Again, it can be seen that the performance gain at the 45-nm node is negligible whereas at 22-nm node it

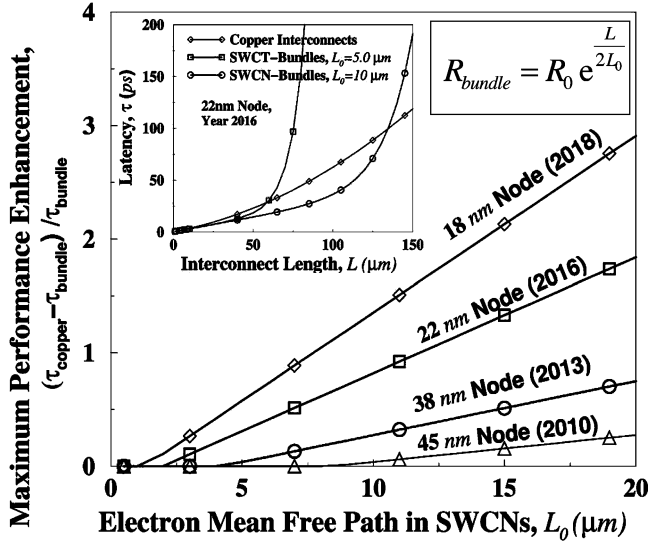


Fig. 2. Inset: Latency versus interconnect length for minimum-sized copper wires implemented at the 22-nm node and bundles of SWCNs with electron mean-free paths of 5 and 10 μm assuming that SWCN resistance increases exponentially with length. For copper interconnects $p = 0$ and $R = 0.5$ are assumed. Main plot: Maximum performance enhancement that can be achieved by using carbon nanotubes versus electron mean-free path in nanotubes for four various generations of technology. At the 22-nm node (year 2016) nanotube bundles can be 30% faster than copper wires for mean-free path of 5 μm , and they can be 80% faster if achieving a mean-free path of 10 μm is feasible.

can be as large as 80% if mean-free paths of around 1 μm are available. It should be noted that mean-free paths longer than 1 μm have already been reported [16], [17].

For large voltage biases (>160 mV), electrons can be backscattered by optical or zone-boundary phonons [18]. Resistance of carbon nanotube interconnects, therefore, increases if the voltage drop along them is large. The relative increase in resistance of nanotubes is a function of the electric field along them. A rigorous analysis that will be published elsewhere shows that for interconnect applications, the electric field inside nanotubes is small enough and the low-bias analysis is quite valid.

V. CONCLUSION

Using physical models, the performances of SWCN and minimum-size copper interconnects are compared for various technology generations. Due to the low density of states in all quantum wires including carbon nanotubes, SWCNs have an extremely large kinetic inductance which causes slow wave propagation. It is therefore critical to use bundles of densely packed nanotubes to improve the wave speed. Carbon nanotubes fabricated so far have shown either linear or exponential resistance increases with length. Analyzing both cases has shown that the performance advantage of nanotube bundles for the 45-nm node (year 2010) is negligible. At the 22-nm node (year 2016), however, nanotube bundles can be 80% faster than copper wires if electron mean-free paths in SWCNs are large enough (1 and 10 μm for linear and exponential dependencies, respectively). Certainly, such a performance enhancement is contingent on many technological breakthroughs including fabrication of bundles of tens-of-micrometers long densely packed nanotubes with small contact resistances.

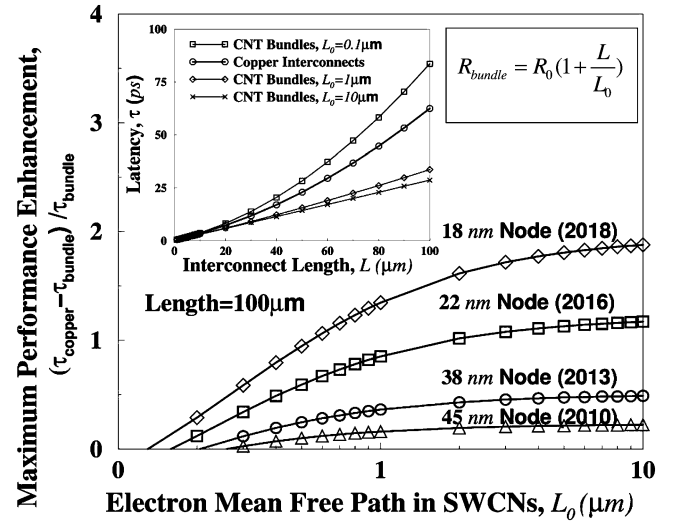


Fig. 3. Inset: Latency versus interconnect length for minimum-sized copper wires implemented at the 22-nm node and bundles of SWCNs with electron mean-free paths of 0.1, 1, and 10 μm assuming that SWCN resistance increases linearly with length. For copper interconnects, $p = 0$ and $R = 0.5$ are assumed. Main plot: Maximum performance enhancement that can be achieved by using carbon nanotubes versus electron mean-free path in nanotubes for four various generations of technology. At the 22-nm node (year 2016) nanotube bundles can be 80% faster than copper wires if they have a mean-free path of 1 μm .

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