

Repeater insertion for carbon nanotube interconnects

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In this reported work, the effects of repeater insertion on the electrical performance of carbon nanotube (CNT) interconnects are studied theoretically. It is shown that the time delay of CNT interconnects, when the length becomes larger than the transition length, can be effectively suppressed by inserting a series of equispaced repeaters. Furthermore, the impact of contact resistance on the repeater insertion is examined and compared. As the single-walled CNT interconnects can endure large contact resistance, its optimal repeater insertion can be determined analytically by neglecting the contact resistances. However, for multi-walled CNT interconnects, the contact resistance must be taken into account in the design of optimal repeater insertion when it exceeds a certain value.

1. Introduction: With the advancement of technology, the interconnect delay has become much larger than the transistor delay, and therefore the 'interconnect era' has been launched [1]. To improve the electrical performance and reliability of conventional Cu interconnects, the carbon nanotube (CNT) has been proposed as a potential material for future interconnect applications [2–7].

The bundled single-walled CNT (SWCNT) interconnect, denoted by b-SWCNT, has been proven to have superior performance over the Cu wire [8]. However, at present, it is still very challenging to realise high quality horizontal b-SWCNTs in large scale with low cost [9]. As an alternative solution, the monolayer SWCNT, that is, m-SWCNT, has been proposed for future interconnects because it possesses smaller capacitance and is much easier for fabrication than the b-SWCNT [10]. It has also been addressed that the multi-walled CNT (MWCNT) is very suitable for the development of interconnects at the intermediate and global levels [11].

On the other hand, it is known that the repeaters have to be employed for long interconnects so as to reduce their time delay [12]. Several studies have been carried out to investigate the repeater insertion methodology for both b-SWCNTs and MWCNTs [13–15]. It is claimed in [13] that the performance improvement by inserting the equispaced repeaters in the b-SWCNT is not as significant as expected, which may be inaccurate as the interconnect length adopted in [13] is too short. Furthermore, it should be noted that the contact resistances must be treated in an appropriate way for the long CNT interconnect architectures since they do exist in each segment, as shown in Fig. 1. Unfortunately, they have been neglected or combined to the total resistance in the design of repeater insertions in [13, 14], which may lead to significant errors. In the work reported in this present Letter, the effects of repeater insertions on the electrical performances of CNT interconnects are studied theoretically, with their contact resistances treated appropriately.

2. Repeater insertion: As shown in Fig. 1, the repeaters are inserted in a long interconnect architecture, which can be made up of Cu, m-SWCNT, b-SWCNT and MWCNT, respectively (see Fig. 2). The repeaters are h times the minimum size, with the output resistance R_{r0}/h , output capacitance hC_{d0} and input capacitance hC_{g0} , where R_{r0} , C_{d0} and C_{g0} are the output

resistance, output capacitance and input capacitance of the minimum-sized repeater, respectively.

The 50% time delay of one segment in the CNT interconnect can be calculated by [12]

$$\tau_{\text{cnt}}(h, k) = 0.69 \left(R_c h C_{g0} + R_{r0} C_0 \right) + 0.69 \left(\frac{R_c c}{2} + r h C_{g0} + \frac{R_{r0} c}{h} \right) \frac{L}{k} + 0.38 r c \left(\frac{L}{k} \right)^2 \quad (1)$$

where r and c are the distributed resistance and capacitance, respectively. The quantum capacitance can be neglected as it is much larger than the electrostatic capacitance, which can be extracted by an electromagnetic simulator (e.g. ANSYS Maxwell). $C_0 = C_{d0} + C_{g0}$ and $R_c = (R_{mc} + R_q)/N_{\text{ch}}$. R_{mc} and R_q ($\sim 12.9 \text{ k}\Omega$) are, respectively, the imperfect and quantum contact resistances per channel. N_{ch} is the total number of conducting channels of the CNT interconnect, and it is given by

$$N_{\text{ch}} = 1000 D_{\text{cnt}} N_{\text{swcnt}} \quad (2)$$

$$N_{\text{ch}} = \sum_{i=1}^{N_{\text{mwcnt}}} (0.0612 D_i + 0.425) \quad (3)$$

where D_i is the diameter of i th-shell in the MWCNT, and N_{mwcnt} is the number of shells. The total time delay is $T(h, k) = k \tau_{\text{cnt}}(h, k)$, and by setting $\partial T / \partial h$ and $\partial T / \partial k$ to be zero, we obtain

$$69 \left(R_{r0} C_0 + R_c C_{g0} h \right) = 38 r c \left(\frac{R_c C_{g0} h^2}{R_{r0} c - r C_{g0} h^2} \right)^2 \quad (4)$$

The optimal value of h , denoted as h_{opt} , can be extracted by solving (4) numerically. Then, the optimal number of segment k_{opt} can be obtained by

$$k_{\text{opt}} = \text{integer} \left[\left(\frac{R_{r0} c}{C_{g0} h_{\text{opt}}^2} - r \right) \frac{L}{R_c} \right] \quad (5)$$

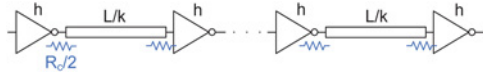


Figure 1 Repeater insertion in a long interconnect architecture of length L , and it is divided into k segments by the repeaters, which are h times as large as the minimum-sized gate

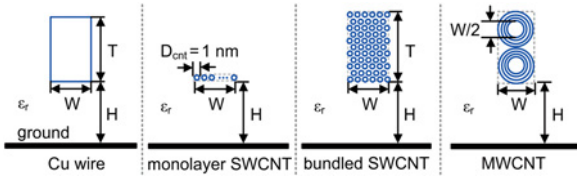


Figure 2 Cross-sectional view of Cu, m-SWCNT, b-SWCNT and MWCNT interconnects

For Cu wires, the specularity and reflectivity parameters are chosen to be 0.5, and the line edge roughness is about 40% [10]. Interval between two adjacent SWCNTs and shells in MWCNT are 0.34 nm, that is, the van der Waals gap, and the fraction of metallic CNTs in the b-SWCNT is assumed to be one-third

Therefore the minimum total time delay $T_{\min} = T(h_{\text{opt}}, k_{\text{opt}})$ can be calculated accordingly. It can be seen that h_{opt} is irrelevant to the length, while k_{opt} increases approximately linearly with the length.

3. Results and discussion: The interconnect parameters of Cu and CNTs at the 14 nm technology node are given in Table 1 [16]. It is observed that the RC ratios of Cu/m-SWCNT and b-SWCNT/MWCNT are close to 1.

3.1. Transition length: Here, L_t is defined as the transition length where the second and last term in $T(h_{\text{opt}}, 1)$ are equal to each other, and

$$L_t = \frac{69}{38} \left(\frac{R_{\text{tr}0}}{rh_{\text{opt}}} + \frac{R_c}{2r} + \frac{C_{g0}h_{\text{opt}}}{c} \right) \quad (6)$$

It means that for the interconnect with length larger than L_t , the time delay increases superlinearly with the length, and the repeater insertion can work effectively. The variable h_{opt} and L_t against R_{mc} for three types of CNT interconnects are plotted in Figs. 3a and b, respectively. The range of R_{mc} is chosen to be $[0, 200]$ k Ω [17]. It is shown that the h_{opt} and L_t decreases and increases with R_{mc} , respectively. Since the MWCNT possesses the smallest N_{ch} among such three types of CNTs, it is most susceptible to the variation of R_{mc} , and $h_{\text{opt}}(\text{MWCNT}) < h_{\text{opt}}(\text{b-SWCNT})$. However, although m-SWCNT has small N_{ch} , it remains nearly unaffected because of its large resistance.

At the 14 nm node, the electrical performances of b-SWCNT and MWCNT interconnects are comparable. Figs. 4a and b show the time delays against the repeater number for the ideally contacted b-SWCNT and MWCNT interconnects with different lengths. Obviously, when $L = 50 \mu\text{m}$ ($< L_t$), the time delays increase almost linearly with the number of repeaters. However, it cannot be

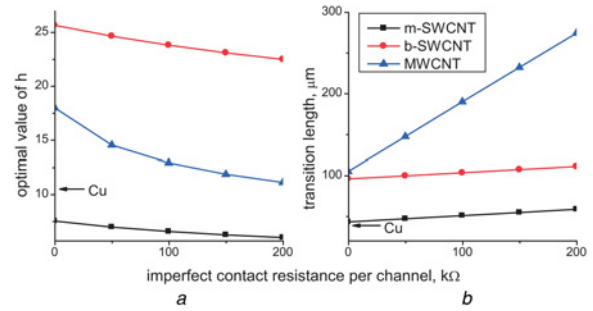


Figure 3 Optimal value of h and transition length against imperfect contact resistance per channel for the CNT interconnects at the 14 nm technology node

a h_{opt} against R_{mc}

b L_t against R_{mc}

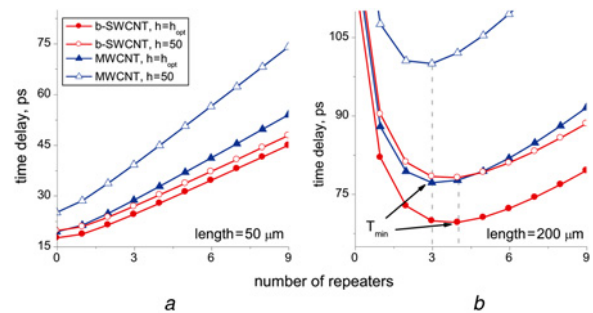


Figure 4 Time delays against repeater number for the ideally contacted b-SWCNT and MWCNT interconnects with different lengths

a 50 μm length

b 200 μm length

simply concluded as presented in [13] that the insertion of equi-spaced repeaters does not work as expected for the b-SWCNT, which actually depends on the interconnect length. When the length increases to a certain limit, the time delay is significantly suppressed by inserting a set of repeaters. As the repeaters are not necessary for short interconnects, we would like to say that the repeater insertion works effectively for the CNT interconnects. The effect of repeater size on the time delay is also shown in Fig. 4. It is evident that the optimal number of repeaters $n_{\text{opt}} (= k_{\text{opt}} - 1)$ remains unchanged with the variation of repeater size. Actually, this is because the contact resistance can be neglected for ideally contacted CNT interconnects. So k_{opt} and h_{opt} become irrelevant with each other, as demonstrated in the following Section.

Table 2 gives the optimal number of repeaters and minimum total time delay of Cu and ideally contacted CNT interconnects with different lengths. The performance advantages of CNT interconnects to their Cu counterpart are proven with the insertion of repeaters implemented. Moreover, n_{opt} of b-SWCNT and MWCNT are

Table 2 Optimal number of repeaters n_{opt} and minimum total time delay $T_{\min}$ of Cu and ideally contacted CNT interconnects at the 14 nm technology node

	$L = 200 \mu\text{m}$		$L = 500 \mu\text{m}$		$L = 1000 \mu\text{m}$	
	n_{opt}	$T_{\min}$, ps	n_{opt}	$T_{\min}$, ps	n_{opt}	$T_{\min}$, ps
Cu	11	170.28	28	425.65	58	851.30
m-SWCNT	9	159.44	25	398.46	51	796.92
b-SWCNT	4	69.52	11	173.64	22	374.24
MWCNT	3	77.13	10	192.75	20	385.38

Table 3 Optimal number of repeaters n_{opt} and minimum total time delay T_{min} of CNT interconnects with $R_{\text{mc}} = 100 \text{ k}\Omega$ at the 14 nm technology node

	$L = 200 \text{ }\mu\text{m}$		$L = 500 \text{ }\mu\text{m}$		$L = 1000 \text{ }\mu\text{m}$	
	n_{opt}	T_{min} , ps	n_{opt}	T_{min} , ps	n_{opt}	T_{min} , ps
m-SWCNT	8	187.96	21	469.78	43	939.56
b-SWCNT	3	75.31	10	188.13	20	376.20
MWCNT	2	129.68	6	323.19	12	645.79

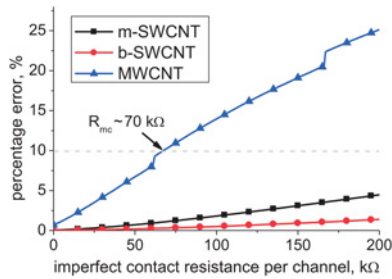


Figure 5 Percentage error against imperfect contact resistance per channel for CNT interconnects with the length of 1000 μm

much smaller than that of Cu, which means that more chip area and power consumption can be saved [11].

3.2. Impact of imperfect contact resistance: As indicated earlier, the impact of R_{mc} needs to be further explored. Table 3 shows the impact of R_{mc} on the optimal number of repeaters and minimum total time delay of CNT interconnects. As R_{mc} increases to 100 k Ω , n_{opt} is reduced slightly, while T_{min} increases as high as 17.9, 8.34 and 68.1% for the m-SWCNT, b-SWCNT and MWCNT interconnects, respectively.

In [14], the optimal values of h and k are calculated analytically by combining R_c to the total resistance, that is,

$$h'_{\text{opt}} = \sqrt{\frac{R_{r0}cL}{R_t C_{g0}}} \quad (7)$$

$$k'_{\text{opt}} = \text{integer} \left(\sqrt{\frac{38R_t cL}{69R_{r0} C_0}} \right) \quad (8)$$

where $R_t = rL + R_c$. As R_c exists in each segment, the percentage error P_{id} caused by this treatment is defined as

$$P_{\text{id}} = \left[\frac{T(h'_{\text{opt}}, k'_{\text{opt}})}{T(h_{\text{opt}}, k_{\text{opt}})} - 1 \right] \times 100\% \quad (9)$$

It is noted that P_{id} can be thought as independent of the length, as the optimal k increases linearly. Here, we take the 1000 μm -long CNT interconnect as an example.

Fig. 5 shows the results of P_{id} against R_{mc} for three types of CNT interconnects. It can be seen that both the m-SWCNT and the b-SWCNT can endure large R_{mc} because of their large intrinsic resistance and N_{ch} , respectively. However, the MWCNT case is very susceptible to the variation of R_{mc} . When R_{mc} is larger than 70 k Ω , significant error is caused by using (7), (8) instead of (4), (5), which

means that the optimal repeater insertion for the MWCNT interconnects must be calculated numerically.

4. Conclusions: The repeater insertions for three types of CNT interconnects have been investigated and compared, with the contact resistance treated appropriately. It is demonstrated that the insertion of repeaters can effectively reduce the time delay for the CNT interconnects. Compared to the Cu wire, the bundled SWCNT and MWCNT have a fewer number of repeaters, which could save chip area and power consumption, significantly. However, as the MWCNT is very sensitive to variation of contact resistance, its optimal repeater insertion should be calculated by considering the impact of contact resistances.

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