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Statistical Analysis of Signal Integrity Issues in CNT Interconnects due to Contact Resistance Variations

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Abstract— Carbon nanotubes have recently been proposed as a possible replacement of metal interconnects in future technologies. These interconnects are supposed to carry signal frequencies above 20GHz by the year 2020. Hence signal integrity analysis is inevitable under real life process conditions. Contact resistance of CNT interconnects are reported to be varying between 0KΩ to 120KΩ. However, no study has been extensively analysed its effect on signal integrity issues for these interconnects. This work aims to fill that gap by Statistical analysis of the impact of contact resistance variations on signal integrity issues of bundles of SWCNTs. This work revealed that the signal integrity issues due to contact resistance variations are more severely effecting signal timing variations than the crosstalk induced signal overshoots and undershoots.

Index Terms—Statistical Analysis, Process variations, Simulation, Signal Integrity, Carbon nanotube, Monte Carlo Analysis, SWCNT, SWCNT Bundles.

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1 INTRODUCTION

CARBON NANOTUBESwere discovered in 1991 by SumicoIijima. These are large macromolecules that are unique because of their shape, size, and remarkable physical properties. Carbon nanotubes are long, thin cylinders of carbon, havingexcellent electrical and thermal properties suitable for IC (Integrated circuits) interconnects. Thus CNT has become the most promising replacement for current interconnects in future VLSI technologies in the nanometer regime [1].

Carbon nanotubes can be classified into single-walled carbon nanotubes (SWCNTs) and multiwalled carbon nanotubes (MWCNTs). There structures are as shown in Fig 1.asSingle or multiple concentrically nested structures. A SWCNT bundle consists of large number of electrically parallel isolated CNTs. The parallel connection resultsin considerable reduction in resistance between the ends of the bundle. Therefore, a CNT bundle makes a better interconnect than the isolated counterparts. Bundled CNTs can be made either with SWCNTs or with MWCNTs. In a bundle, some of the constituent CNTs are metallic while others may be semiconducting. From the interconnect perspective only metallic ones are relevant.

These interconnects are intended to carry signal frequencies beyond 20GHz by the year 2020. The frequencies are in microwave range and may introduce different signal integrity issues. Total system performance and reliability can significantly degrade due to signal integrity issues, such as reflections, crosstalk, frequency dependent transmission line losses and dispersion.

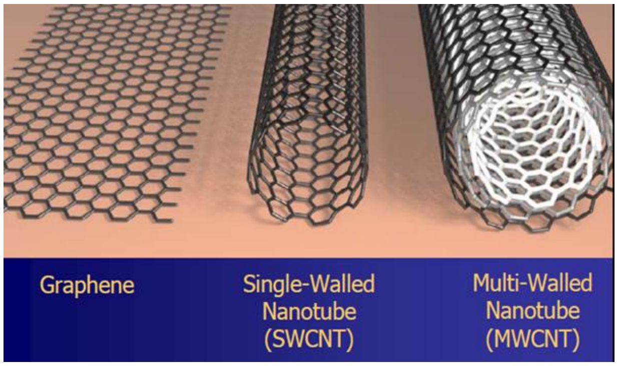

Fig. 1.a) Graphite lattice. (b) single-walled CNT. (c) multi-walled CNT [2]

Research works on signal integrity issues are in budding stage [3]. A work on crosstalk analysis of CNT interconnects was reported in [3]. This work revealed that delay and voltage noise margins in MWCNT interconnect are much better than SWCNT interconnect. The crosstalk delay is lower in the SWCNT interconnect. In these interconnect crosstalk delay can be improved by optimizing the spacing between the interconnects. They had proposed a crosstalk aware CNT bus architecture. This is formed by double walled carbon nanotubes (DWCNT) in parallel. It is shown to have significantly less cross talk due to delay and noise voltage peaks. The crosstalk effect in SWCNT and DWCNT interconnects have been analyzed. The analytical crosstalk models were developed to capture crosstalk, delay, glitches etc. with good accuracy. Crosstalk induced delay in SWCNT and DWCNT bundle interconnects were compared with that of copper interconnect. It is observed that for semi-global and global interconnects CNT especially DWCNT results in much reduced crosstalk induced signal delay. The crosstalk induced voltage peaks may pro-

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duce stress in oxide layers underlying the victim interconnect. The possibilities of oxide damage due to crosstalk overshoot and undershoot was studied by [6]. They had observed that with scaling ratio of overshoot/undershoot voltages to power supply voltage does not vary along with scaling in all types of interconnects. In case of the CNT based interconnects neither scaling nor increase in length affect crosstalk induced voltage overshoot and undershoot. However, no study has extensively analyzed the effect of crosstalk induced overshoot under process variations. Process variation has recently emerged as a major concern in the design of VLSI circuits including interconnects. The process variations such as variations of coupling capacitance and contact resistance, which are two highly varying system parasitic effects, lead to uncertainties of circuit performances such as propagation delay and signal integrity issues due to crosstalk.

All above reported works have taken the value of the contact resistance as zero [2,3]. In reality, it is very difficult to make a good contact with a CNT. The unavoidable contact imperfection increases in the range 0KΩ-120KΩ have been reported [7]. This work aims to analyze the impact of contact resistance variations due to process immaturity on signal integrity of Carbon Nanotube Interconnects in real time perspective.Section 2 discusses the preliminary Electrical models of CNT interconnects used for analysis. Section 3 discusses problem statement and its solution methodology. Results are discussed in section 4. Conclusion remarks are discussed section 5.

2 ELECTRICAL MODEL FOR CNT INTERCONNECTS

An interconnect can be modeled as either lumped or distributed form of Resistance-Capacitance (RC) or Resistance-Capacitance-Inductance (RLC) [4]. A T ladder circuit models are proposed to simulate the distributed RC line with relative error of the delay is less than 3 percent even in the worst case [5]. The electrical circuit model parameters of SWCNT and SWCNT Bundles are explained as follows.

The CNT resistance is modeled by three parts. 1) Contact resistance (R_C), 2) Quantum resistance (R_Q) and 3) Ohmic resistance (R_O) respectively which is given by [6]

$$\mathrm{R_{CNT}} = R_C + R_Q + R_O \ \text{ for } l_{CNT} > \lambda \qquad (1)$$

$$\mathrm{R_{CNT}} = R_C + R_Q \ \text{ for } l_{CNT} \le \lambda \qquad (2)$$

Where$l_{CNT}$is the length of SWCNT and λ is the mean free path (MFP) of electron[6].

The resistance of a SWCNT contains imperfect contact resistance (R_C) which is in the range of 0 to 120KΩ, Quantum resistance (R_Q),

$$R_0 = \frac{\mathrm{h}}{4\mathrm{e}^2} (3)$$

Where h is Planck'sconstant,e is the charge of an electron, and $\lambda_{CNT}$is the mean free path length[8].

Ohmic resistance (R_O) [6]

$$R_O = R_Q \cdot (l_{CNT}/\lambda) \qquad (4)$$

Quantum resistance R_Q=6.45kΩ, Ohmic resistance R_O=6.45 kΩ [8]

The capacitance of a SWCNT includes electrostatic capacitance (C_E) and quantum capacitance (C_Q); The expressions are given by [8]

$$C_E = 2\pi\varepsilon \,/\, (\ln(\mathrm{y/D})) \qquad (5)$$

For D=1nm, y=1μm, C_E ≈50 aF/μm.[8]. This is the intrinsic capacitance of an isolated CNT w.r.t. ground plane.[10],where D is the diameter, y is the distance away from a ground plane treating the CNT as a thin wire,

$$C_Q = (2e^2)/hV_F \qquad (6)$$

andV_F is the Fermi velocity[8].

The effective capacitance $C_{bundle}$of the series combination of a quantum and electrostatic capacitance is given by [10]

$$\frac{1}{C_{bundle}} = \frac{1}{C_Q^{bundle}} + \frac{1}{C_E^{bundle}} (7)$$

The inductance of a SWCNT includes kinetic inductance (L_K) and magnetic inductance (L_M); The expressions are given by [8]

$$L_k = h/2e^2V_F \qquad (8)$$

and

$$L_M = \mu^2\pi\ln(\mathrm{y/D}) \qquad (9)$$

For D=1nm and y=1 μm, L_M(per unit length) this evaluates to≈1.4 pH/μm. On the other hand, L_K(per unit length) for a CNT evaluates to 16nH/μm [9].

Due to the low density of current carriers in nanotubes there is a large kinetic energy stored in the current flow, therefore a CNT has a dominant kinetic inductance, the magnetic inductance can even be neglected as it is many orders smaller [9],[10]. The inductance of a SWCNT bundleis given by the parallel combination of the inductances corresponding to each CNT forming the bundle, we have

$$L_{bundle} = \frac{L^{CNT}}{n_{CNT}} \qquad (10)$$

where$L^{CNT}$is the magnetic inductance of an isolated SWCNT.

TABLE 1
RESISTANCE, INDUCTANCE, CAPACITANCE AND COUPLING CAPACITANCE OF SWCNT BUNDLE BASED INTERCONNECT FOR DIFFERENT LENGTHSAND WITH DIFFERENT METALLIC FRACTIONS [6]

PARAMETERS	Length (um)	SWCNT Bundle Pm=1/3	SWCNT Bundle (Pm=1)
Resistor(kΩ)	1	0.7784	0.2595
	5	0.8869	0.2956
	10	1.015	0.3383
Inductance(nH)	1	0.0235	0.0077
	5	0.1178	0.0387
	10	0.2357	0.0775
Capacitance (fF)	1	0.837	1.046
	5	4.185	5.23
	10	8.37	10.46
Coupling capacitance(fF)	1	0.05	0.05
	5	0.252	0.252
	10	0.252	0.505

A Schematic view of CNT equivalent circuit used for crosstalk analysis between the adjacent nets is shown in Fig 2. Nets are modeled as symmetrical T-type RLC network [6].

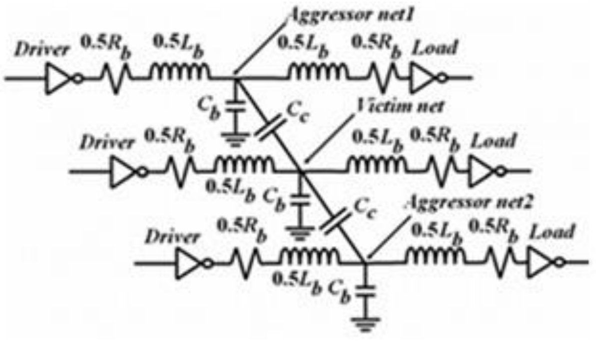

Fig. 2. Symmetrical T-structured ESC model [6].

3.REAL LIFE ANALYSIS ON SIGNAL INTERGRITY ISSUES

Real life effect of contact resistance variations are evaluated using Monte Carlo analysis. Monte Carlo simulation is a technique used to understand the impact of uncertainty in different forecasting models. Monte Carlo analysis performs numerous simulations with different boundary conditions. It chooses randomly different process parameters within the worst case deviations from the nominal conditions for each run and allows statistical interpretation of the results. In this method, a random value is selected for each run, based on the range of estimates. Thereby it mimics the real life conditions.

The schematic diagram of equivalent RLC model used for this analysis is given in Fig 3 Here contact resistance R_C is modeled as a Monte Carlo element. In order to analyse the crosstalk induced noise effects in an interconnect, geometry of three parallel lines is considered [7]. The wire affected by the crosstalk is termed as victim wire, and the wires that cause crosstalk on the victim wire are termed as aggressor wires. To analyze the worst case crosstalk induced noise situation, it is assumed that there is no voltage in the signal line, and the input excitation of the aggressor lines on each side are square wave signal of 1V with simultaneous switching in the same direction. For overshoot, rise time and fall time analysis, the victim net is kept fixed at logic 1 and 0 levels, respectively. The aggressor nets are switched from logic 0→1 and logic 1→0 [6]. Different values of mean, median and sigma were obtained by varying the conditions of two aggressors and victims.

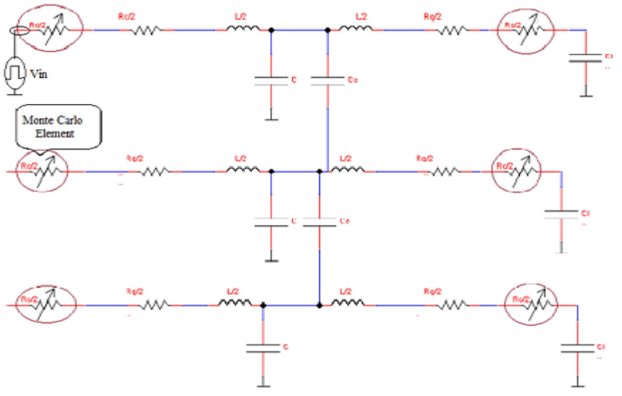

Fig. 3. Symmetrical T-structured ESC model for CNT interconnect with Rc modeled as a Monte Carlo element.

The different conditions that are taken for timing analysis

1. Victim switches from logic 0→1; Both aggressors are grounded
2. Both aggressors1 and aggressor2 and victim switches from logic 0→1
3. Both aggressor2 and victim switches from logic 0→1; Aggressors1 switches from logic 1→0
4. Both aggressors1 and aggressor2 and victim switches from logic 1→0

This work has also evaluated the impact of contact resistance variations on signal integrity issues. Simulation results shown below are obtained by providing a pulse source of 1V [0→1/1→0] having 20 GHz frequency at the input node of the aggressor nets and DC 1V/0V at the victim input node of the above circuits.

4 RESULTS AND DISCUSSION

Timing and crosstalk analysis due to contact resistance variations were analyzed and its results are discussed below. The mean value, median and sigma values have given the general information, central tendency and standard deviations respectively.

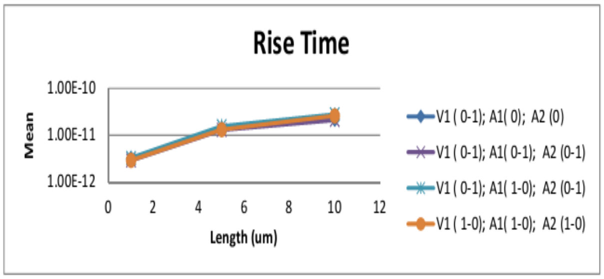

Fig. 4. Mean of rise time of densely packed SWCNT

Fig 4 shows that as the variations in propagation delay of CNT with contact resistance. The mean of rise time increases with the length of interconnect for different conditions. The deviations were more in lower lengthsof interconnects since the magnitude of the total resistance is controlled by the contact resistance. The similar graphs were obtained for sparsely packed SWCNT.

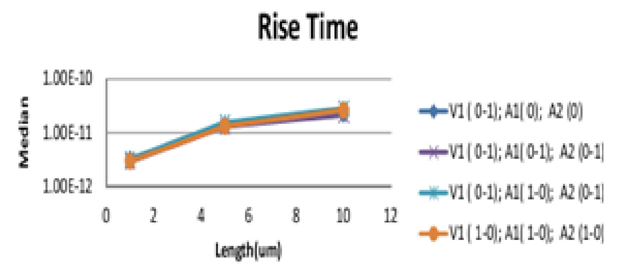

Fig. 5. Median of rise time of densely packed SWCNT.

Fig 5 shows that the median of rise time with the length of interconnect. Median is a measure of the central tendency. The tendency of deviation for mean and median is almost same.

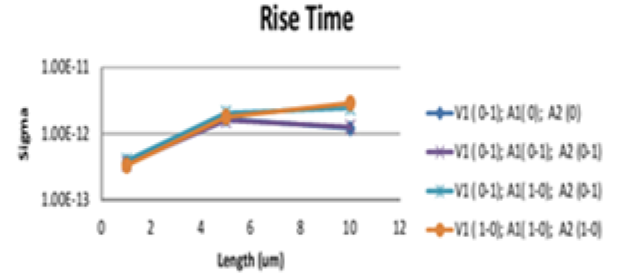

Fig. 6. Sigma of rise time of densely packed SWCNT

Fig 6 shows that the standard deviation of rise time of densely packed SWCNT increases exponentially at the lower level of the interconnect. From the Fig 6 it can be interpreted that the rise time fluctuations are a function of signaling nature and length.

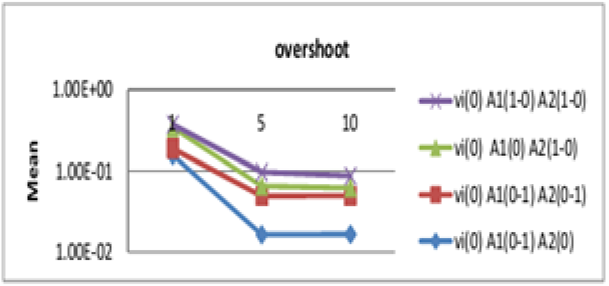

Fig. 7. Mean overshoot of densely packed SWCNT

Fig 7 shows that the mean overshoot of densely packed SWCNT. The overshoot voltage is severe in lower levels of interconnects when the victim is grounded. The overshoot voltage decreases and become a constant as the length increase. The magnitude of overshoot voltage varies with different conditions. As length of the interconnect increases, total resistance of interconnect is dominated by quantum resistance and scattering resistance. Hence the signal integrity issues due to contact resistance variations are reduced as length increases. This is due to the fact the total resistance of CNT interconnects are dominated by the effect of contact resistance which occurs only at lower lengths.

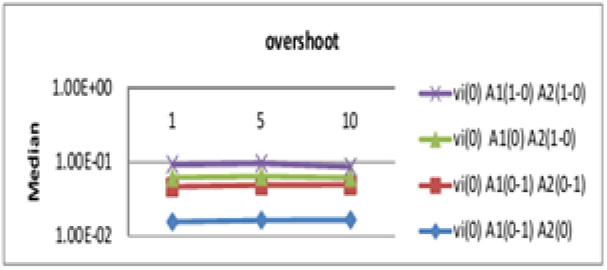

Fig. 8. Median overshoot of densely packed SWCNT

Fig 8 shows that the median overshoot of densely packed SWCNT is constant and the magnitude varies only with switching conditions of aggressors. The median is the middle of a distribution, which is less sensitive to extreme values.

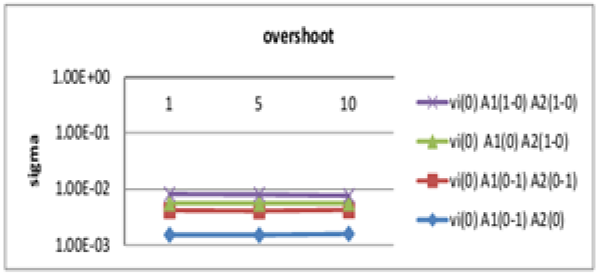

Fig. 9. Sigma overshoot of densely packed SWCNT

Standard deviation shows that how much variation from mean, or expected value are possible. A low standard deviation indicates that the data points tend to be very close to the mean; high standard deviation indicates that the data points are spread out over a large range of values. From the Fig 9 it can be interpreted that the fluctuations are less and magnitude varies with the state of the aggressors conditions.

5 CONCLUSION

In this paper we have studied the crosstalk induced signal integrity an issue of various CNT interconnects and the impact of contact resistance variations by Monte Carlo Analysis.From the result obtained, we infered that the overshoot voltage and undershoot voltage existing in SWCNT bundle is due to contact resistance. Since the magnitude of this voltage is less than 30%, it would not affect significantly. The overshoot/undershoot voltage is severe in local interconnects due to contact resistance. The SWCNT bundle is best for intermediate and global interconnects. This uncertainty level in the signal integrity issues can be minimized only with maturity in the fabrication technology for providing perfect contacts.

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