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Analysis of Various Parameters of Mixed Carbon Nanotube Bundle for Interconnect Applications

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Abstract

Metallic Carbon nanotubes (CNTs) have received much attention for their unique characteristics as a possible alternative to Cu interconnect. Owing to these scattering phenomena resistivity of Cu begins to increase. This drives us to look for new materials for future very large scale integration (VLSI) interconnects. Carbon nanotubes have superior properties like current carrying capacity and conductivity compared to Cu interconnect. It exhibits metallic or semi-conducting property depending on chirality.

Mixed Carbon nanotube (MCNT) bundle is the mixture of single - wall carbon nanotubes (SWCNTs) and multi- wall carbon nanotubes (MWCNTs). By varying Bundle length, Bundle width, Shell-spacing and Average diameter, we analyze the circuit parameters such as resistance, capacitance, inductance, conductance and propagation delay. Also the effect of temperature variations to these parameters was also studied. The simulations have been carried out by using carbon nanotube interconnect analyzer (CNIA) tool.

1. Introduction

The ever shrinking size in commercially integrated circuits has now reached the nanoscale limit and its continuous scaling beyond the 90nm node has proved to be a great challenge. It is well recognized that, there are difficulties in producing reliable materials with controlled properties at this scale, as quantum effects such as tunneling and contact resistance may severely affect the performance of these smaller nanoelectronic devices. The role of interconnect in an integrated circuit is to enable effective passing of clock and other signals in addition to providing power to various parts of the circuit on a chip.

Copper, which is presently used as the interconnect material, faces two critical problems: one related to its inability to carry high current density and the other being its increased electrical resistivity due to surface scattering of electrons, and problems due to grain boundaries. It should be pointed out that the electronic transport through copper wires at the nanoscale requires a full quantum mechanical description and the present understanding of the increase in the resistance of copper wires with decreasing dimension. However copper faces problems so that an alternative to copper called “Carbon nanotube” a very good conductor which is one hundred times the tensile strength of steel, thermal conductivity better than all but the purest diamond, and electrical conductivity similar to copper, but with the ability to carry much higher currents, they seem to be a wonderful material for ICs in place of copper. The changes in resistance, capacitance, inductance, propagation delay during interconnect scaling poses a serious challenge to the performance and reliability of the VLSI circuits. The effect of temperature to these parameters should be considered in application as it can directly influence the device performance.

2. Carbon Nanotubes

Carbon nanotubes were discovered in 1991 by Sumio Iijima of NEC. Carbon nanotubes are alternative to copper because of their remarkable conductive, mechanical and thermal properties [2], [4]. They are effectively long, thin cylinders of graphite. Graphite is made up of layers of carbon atoms arranged in a hexagonal lattice, like chicken wire. Carbon nanotubes are the strongest and most flexible molecular material because of C-C covalent bonding and seamless hexagonal network architecture. With one hundred times the tensile strength of steel, thermal conductivity (~ 3000W/mK in axial direction) better than all but the purest diamond, Young's modulus of over 1TPa vs 70 Gpa for Aluminium, Maximum strain ~ 10% much higher than any material and electrical conductivity six orders of magnitude higher than copper and with the ability to carry much higher currents, it seems to be a wonder material. It can be metallic or semiconducting depending upon chirality, i.e., it has a tunable bandgap. The highest quality carbon nanotube films we have developed achieve roughly 90% visible-light transmittance and about 200 Ω/□ sheet resistance *R*S. There are six types of carbon nanotubes, of which mostly used single-walled and Multi-walled nanotubes. They are Long, Short, Single-walled, Multi-walled, Open and Closed types.

The structure of carbon nanotubes consist of one or more coaxial cylindrical sheets of graphite with an aspect ratio typically greater than 100 and outer diameter measuring tens of nanometer and closed at ends with two semi domes. Essentially two families of carbon nanotubes exist:

(1) Single walled nanotubes (SWNT), made up of only one straight tubular unit [5]. It is fundamental form of carbon nanotube. Single-walled nanotubes are 1 to 2 nm in diameter and combine to form rope-like structures. The lengths of the ropes are difficult to determine but are approximately 1 µm long, with diameters ranging from 10 to 30 nm. The theoretical minimum diameter of a carbon nanotube is around 0.4 nanometers, which is about as long as two silicon atoms side by side, and nanotubes this size have been made. Average diameters tend to be around the 1.2 nanometer mark, depending on the process used to create them. The aspect ratio (length divided by diameter) is typically greater than 100 and can be up to 10,000. SWNTs are more applicable than their multi-walled counterparts and can be twisted, flattened and bent into small circles or around sharp bends without breaking.

(2) Multi walled nanotubes (MWNT), made up of series of coaxial tubes 0.34 nanometer apart. The different SWNTs that form the MWNT may have quite different structures. The tubes involved typically have 8 to 15 walls and are around 10 nanometers wide and 10 micrometers long. MWNTs are typically 100 times longer than they are wide and have outer diameters mostly in the tens of nanometers.

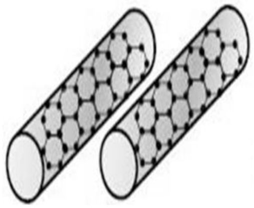


Fig 1.(a) Single walled CNT

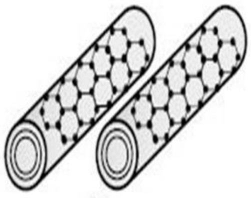


Fig 1.(b) Multi-walled CNT

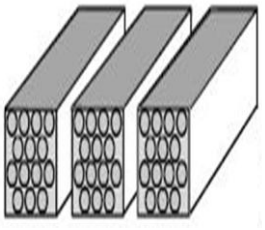


Fig 1. (c) Single walled CNT bundle

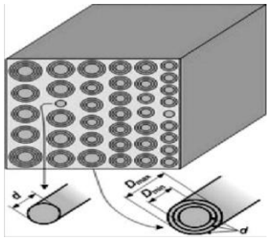


Fig 1. (d) Mixed CNT bundle

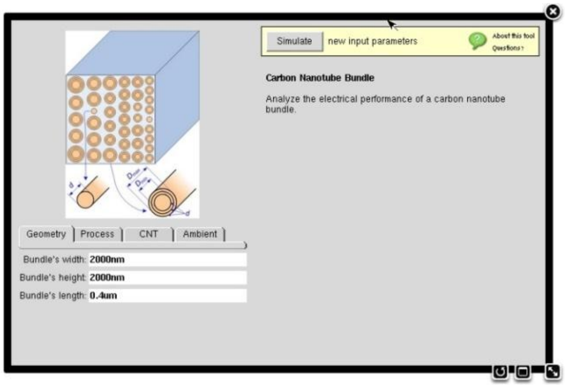
Any carbon nanotubes can be represented with indices (n,m) where n,m are two integers. CNT can either be metallic or semiconducting. Depending on whether the tube is wrapped as a simple cylinder or a tighter helical form, the nanotube material can possess the properties of a semiconductor or a metallic material. The electrical behaviour of CNTs can be determined from the following simple rule which states that the difference between the indices of the tube should be an integral multiple of three. Mathematically, it can be stated that if $(n-m) = 3q$ then it is metallic and if $(n-m) \neq 3q$ then it is semiconducting where q is an integer.

Carbon nanotubes also exist in the form of bundles. CNT-bundle interconnect is assumed to be composed of hexagonally packed metallic carbon nanotubes within the same sheath. They are of two types, either it can be single walled carbon nanotubes bundle or mixed carbon nanotubes bundle.

(a) SWNT bundle consists of a number of single walled carbon nanotubes closely packed within a sheath.
(b) Mixed CNT bundle consist of both single walled carbon nanotubes and Multi walled carbon nanotubes closely packed within the same sheath.

3. Carbon Nanotube Interconnect Analyser (CNIA)

CNIA was the simulation software used for studying the variation in parameters of Mixed CNT bundle. This simulator has four windows for varying inputs named as Geometry, Process, CNT and Ambient. The Geometry consists of parameters like Bundle's width, height and length; Process consists of Density, Average diameter, Standard deviation of diameter, Inner to outer diameter ratio and probability of metallic CNTs; CNT consists of Carbon to carbon spacing, Shell spacing and Tight binding energy; Ambient consist of temperature of the process. For our study, among these input parameters six parameters are selected. They are Bundle length(L) in nm, width(W) in nm, height(H) in nm, Average diameter(D) in nm, Shell Spacing(S) in A^o and Temperature(T) in Kelvin. It is also considered that Bundle width is equal to bundle height.



Carbon Nanotube Bundle

Analyze the electrical performance of a carbon nanotube bundle.

Bundle's width: 2000nm
Bundle's height: 2000nm
Bundle's length: 0.4um

Fig 2. CNIA simulation software

The various output parameters for study are Resistance in ohms, Capacitance in Farads, Inductance in Henry, propagation delay Pico seconds and the total number of conducting channels. This simulation software is available in the website www.nanohub.org.

4. Results

4.1. Resistance

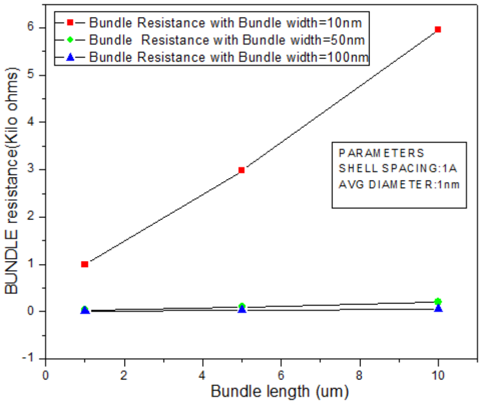


Fig 3.(a) Resistance for variation in bundle length & width

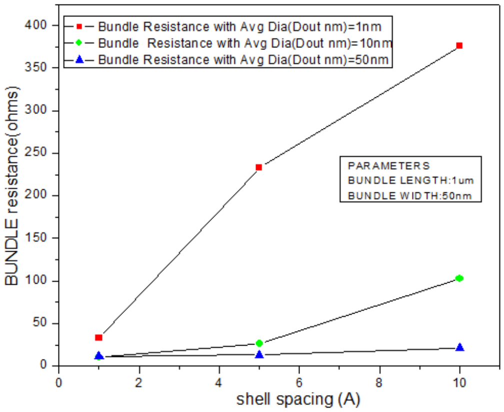


Fig 3.(b) Resistance for variation in shell spacing & Avg. Diameter

From the above figure, the resistance of mixed carbon nanotube bundle decreases with decrease in length, increase in bundle width, decrease in shell spacing and increase in average diameter.

4.2. Capacitance

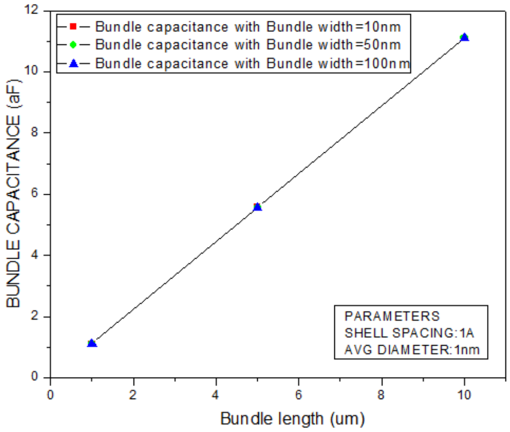


Fig 4.(a) Capacitance for variation in bundle length & width

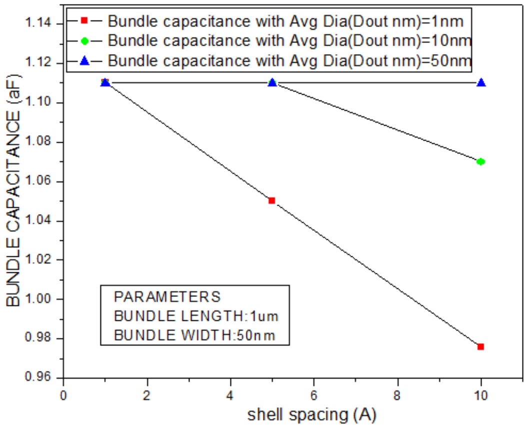


Fig 4.(b) Capacitance for variation in shell spacing & Avg. Diameter

From the above figure, the capacitance of mixed carbon nanotube bundle decreases with decrease in length and no change with variation in bundle width. Also, it decreases with increase in shell spacing and decrease in average diameter.

4.3. Inductance

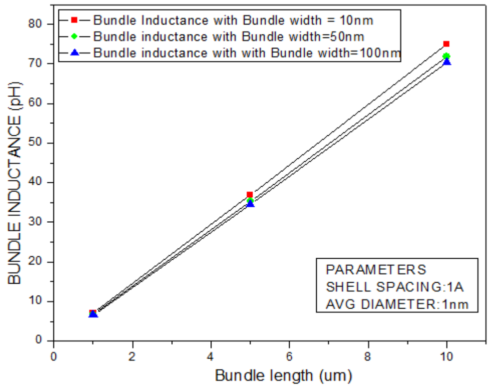


Fig 5.(a) Inductance for variation in bundle length & width

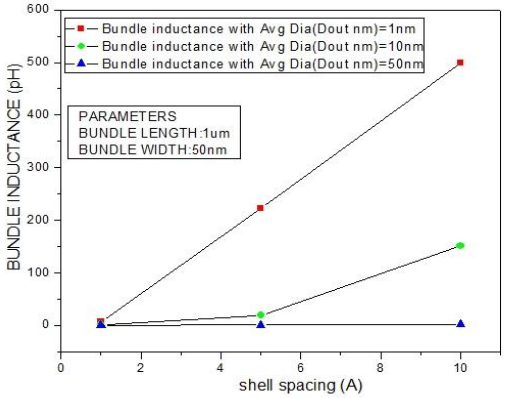


Fig 5.(b) Inductance for variation in shell spacing & Avg. Diameter

From the above figure, the inductance of mixed carbon nanotube bundle decreases with decrease in length, increase in bundle width, decrease in shell spacing and increase in average diameter.

4.4 Propagation delay

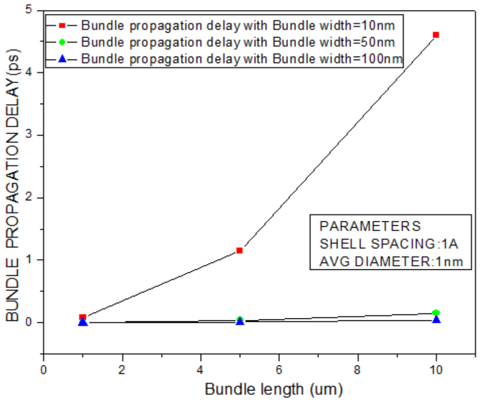


Fig 6.(a) Propagation delay for variation in bundle length & width

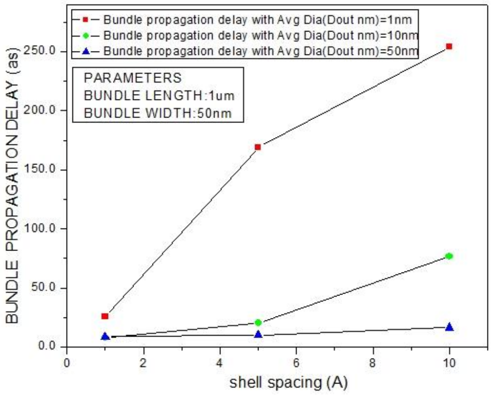


Fig 6.(b) Propagation delay for variation in shell spacing & Avg. Diameter

From the above figure, the propagation delay of mixed carbon nanotube bundle decreases with decrease in length, increase in bundle width, decrease in shell spacing and increase in average diameter.

5. Conclusion

The resistance, capacitance, inductance and propagation delay of mixed carbon nanotube bundle were analysed in this paper. For better performance when used in interconnect applications, these four parameters must be kept minimum. The various results show that it is always better to minimize the length and shell spacing while maximize the width and average diameter of Mixed CNT bundle.

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