Perfromance analysis of cnt interconnects biology essay

Science, Biology

Chapter 3

The resistance of copper interconnects, with cross-sectional dimensions of the order of the mean free path of electrons (~40 nm in Cu at room temperature) in current and imminent technologies, is increasing rapidly under the combined effects of enhanced grain boundary scattering, surface scattering and the presenceof the highly resistive diffusion barrier layer. The steep rise in parasitic resistance of copper interconnects poses serious challenges for interconnect delay (especially at the global level where wires traverse long distances) and for interconnect reliability, hence it has a significant impact on the performance and reliability of VLSI circuits. In order to alleviate such problems, changes in the material used for on-chip interconnections have been sought even in earlier technology generations, for example the transition from aluminium to copper some years back. Carbon nanotubes have recently been proposed as a possible replacement for metal interconnects in future technologies. Carbon nanotubes (CNTs) are graphene sheets rolled up into cylinders with diameter of the order of a nanometer. Depending on the direction in which CNTs are rolled up (chirality), they demonstrate either metallic or semi-conducting properties. Because of their extremely desirable properties of high mechanical and thermal stability, high thermal conductivity and large current carrying capacity, CNTs have aroused a lot of research interest in their applicability as VLSI interconnects of the future. However, the high resistance associated with an isolated CNT (greater than 6. 45 KΩ) necessitates the use of a bundle (rope) of CNTs conducting current in parallel to form an interconnection. Moreover, due to the lack of control on chirality, any bundle of CNTs consists of metallic as well as semi-conducting nanotubes (the semi-conducting CNTs do not contribute to current conduction in an interconnect).

3. 2 Single Wall CNT (SWCNT) Interconnect

The analysis of SWCNT interconnect is carried using PSIPCE simulations. An equivalent circuit of a SWCNT is taken as given in the reference papers and the equivalent R, L and C parameters are calculated manually from the theoretical formulae and are plugged in the equivalent circuit and the simulations are run. The resulting delay is tabulated and studied for various lengths of interconnects

3. 2. 1 Isolated SWCNT

Resistance of Isolated SWCNT-

The conductance of a carbon nanotube is evaluated using the two-terminal Landauer-Buttiker formula. This formula states that, for a 1-D system with N channels in parallel, the conductance G=(Ne2/h)T, where T is the transmission coefficient for electrons through the sample. Due to spin degeneracy and sublattice degeneracy of electrons in graphene, each nanotube has four conductingchannels in parallel (N= 4). Hence the conductance of a single ballistic single-walled CNT (SWCNT) assuming perfect contacts (T= 1), is given by 4e2/h = 155 µS, which yields a resistance of 6. 45 KΩ. This is the fundamental resistance associated with a SWCNT that cannot be avoided. As shown in Fig 3. 1, this fundamental resistance (RF) is equally divided between the two contacts on either side of the nanotube.---(1)The mean free path of electrons (the distance across which no scattering occurs) in a CNT is typically 1 µm. For CNT lengths less than 1 µm, electron transport is essentially ballistic within the nanotube and the resistance is independent of length (6. 45 KΩ). However, for lengths greater than the mean free path, resistance increases with length as shown in Equation 2 , where L0 is the mean free path and L is the length of the CNT. This has also been confirmed by experimental observations. In the equivalent circuit, this additional scattering resistance would appear as a distributed resistance per unit length to account for resistive losses along the CNT length.---(2)In practice, the observed d. c. resistance of a CNT (at low bias) is much higher than the resistance derived above. This is due to the presence of imperfect metal-nanotube contacts which give rise to an additional contact resistance. As observed in , making a reliable contact to a CNT is very challenging, and the resistance arising from these imperfect contacts is often so high that it masks the observation of intrinsic transport properties. The observed resistance for CNTs has typically been in the range of 100 KΩ, although in a few cases the lowest observed resistance has been seen to approach the theoretical limit of ~7 KΩ. In the equivalent circuit, this additional imperfect contact resistance would appear in series with the fundamental resistance (RF) divided equally among the two end contacts as shown for RF. The total resistance of a CNT is then expressed as the sum of resistances arising from the above three aspects: the fundamental one-dimensional system (CNT) contact resistance, scattering resistance and the imperfect metal-nanotube contact resistance. Evidently the resistance associated with an isolated CNT is too high for realizing an interconnection. Hence, a bundle/rope of CNTs is needed that has much lower effective resistance and may work effectively as an interconnection. Fig 3. 1 Equivalent Circuit of Isolated SWCNT

Capacitance of Isolated SWCNT-

The capacitance of a CNT arises from two sources. The electrostatic capacitance (CE) is calculated by treating the CNT as a thin wire, with diameter ‘ d’, placed a distance ‘ y’ away from a ground plane, and is given by the formula in Equation 3 (CE per unit length) for y> 2d. The quantities y and d are shown in Fig 3. 2 For d= 1 nm, y= 1 µm, CE ≈30 aF/um. This is the intrinsic plate capacitance of an isolated CNT--(3)Fig 3. 2 Isolated conductor, with diameter ‘ d’, over a ground planeat a distance ‘ y’ below it. The quantum capacitance (CQ) accounts for the quantum electrostatic energy stored in the nanotube when it carries current. Due to the Pauli exclusion principle, it is only possible to add electrons into the nanotube at an available quantum state above the Fermi energy level. By equating this energy to an effective capacitance, the expression for the quantum capacitance (per unit length) is obtained as shown in Equation 4, where h is the Planck’s constant and vF is the Fermi velocity. For a carbon nanotube (vF ≈ 8x105m/s), CQ≈100aF/um.---(4)As a CNT has four conducting channels as described in the previous sub-section, the effective quantum capacitance resulting from four parallel capacitances CQ is given by 4CQ. The same effective charge resides on both these capacitances (CE and 4CQ) when the CNT carries current, as is true for any two capacitances in series. Hence these capacitances appear in series in the effective circuit model shown in Fig 3. 1.

Inductance of an Isolated CNT-

The inductance associated with an isolated SWCNT can be calculated from the magnetic field of an isolated current carrying wire some distance away from a ground plane, as depicted in Fig 3. 2. In addition to this magnetic inductance (LM), the kinetic inductance is calculated by equating the kinetic energy stored in each conducting channel of the CNT to an effective inductance. The four parallel conducting channels in a CNT give rise to an effective kinetic inductance of LK/4. The expressions for LM and LK are shown in Equation 8 below.---(5)For d= 1 nm and y= 1 um, LM (per unit length) evaluates to ≈1. 4 pH/um. On the other hand, LK (per unit length) for a CNT evaluates to 16 nH/um. However, the kinetic inductance (LK) is derived considering no potential drop along the nanotube; hence it must be treated with care. Since LK>> LM, the inclusion of LK can have a significant impact on the delay model for interconnects. In the light of experimental evidence of potential drop appearing along the length of a nanotube , LK is excluded from the calculations in this work. This is further justified by the experimental measurements of the high frequency characteristics of carbon nanotubes recently reported in, wherein the large inductive effects expected due to LK are not observed up to frequencies as high as 10 GHz and the high frequency response is effectively damped by the nanotube resistance.

3. 2. 2 Bundle of SWCNT (100)

Resistance of bundle-

The effective resistance of a CNT-bundle with nCNT is given by---(6)It is assumed here that the interaction between adjacent CNTs of a bundle is weak. Experiments on CNT bundles have shown a large temperature-independent coupling resistance (~ several MΩ for defect-free nanotubes), characteristic of direct tunnelling between the nanotubes. Hence, the CNTs of a bundle are only weakly coupled and can be safely assumed to carry currents independent of each other. Temperature dependence of CNT bundle resistance: The resistance of a 3-µm-long isolated metallic SWCNT has been shown to increase super linearly with temperature from about 50 to 290 K. This nonlinearity has been attributed to optical phonon absorption in a temperature-dependent model with very large increase in resistance predicted for longer CNTs in the range of 400 K (typical on-chip temperatures), although this is not supported by data. On the other hand, measurements on SWCNT bundles have consistently shown linear increase in resistance with temperature for temperatures as high as 580 K over a wide range of CNT bundle lengths. The calculated rate of change of resistivity with temperature for a densely packed SWCNT bundle is dρ/dT = 0. 005 µΩ·cm/K, while experimental measurements have shown dρ/dT ~ 0. 1 µΩ·cm/K. The discrepancy apparently arises from the presence of semiconducting CNTs as well as from inter-CNT interactions shows that, for these values of dρ/dT, SWCNT bundle resistance increases by about 10% from room temperature to 400 K (Cu resistance increases by about 40% in the same temperature range).

Capacitance of Bundled SWCNT-

In order to calculate the equivalent capacitance of an SWCNT bundle, we assume that the nCNT nanotubes in the bundle are non-interacting and carry equal currents independent of each other. Under this assumption, the SWCNT bundle is composed of 4n CNT 1-D conductors (each nanotube contributes four 1-D channels). For an SWCNT bundle, the effective quantum capacitance is given by---(7)The electrostatic capacitance of a CNT, CE , can be found by considering it as a thin cylindrical wire and is dependent on its surrounding environment. The expression for CE (per unit length) is given by---(8)For d = 1 nm, y = 1 µm, CE≈ 30 aF/µm. Electrostatic Capacitance of an SWCNT Bundle-Two immediately adjacent wires (left and right, held at ground potential) parallel to the CNT bundle are considered. Top and bottom ground planes represent the orthogonal metal layers, although electrostatic coupling to adjacent (left/right) interconnects is dominant for wires with aspect ratio t/w > 1. For the electrostatic analysis, each CNT is treated as a metal with equal potential over the tube. For the sake of simplicity, it is assumed that all CNTs are held at the same potential. This assumption is valid only when the contacts to all nanotubes within a bundle are identical and each CNT has the same mean free path. Under this assumption, the coupling capacitance between adjacent CNTs in the same bundle does not come into play. The effective capacitance of an SWCNT bundle interconnect (Cbundle) is given by the series combination of its electrostatic capacitance and quantum capacitance. The effective SWCNT bundle capacitance is nearly equal to its electrostatic capacitance and the effect of the quantum capacitance is small.

Inductance of SWCNT Bundle-

In this project, we have assumed non-interacting nanotubes since very little is known about the nature of the electromagnetic interactions in dense CNT bundles. Although SWCNTs in a bundle may not be isolated from each other, the consequences of this for the density of states, conductivity, and magnetically induced currents are not known yet. While the high-frequency properties of individual nanotubes as well as capacitive interactions between adjacent nanotubes in a flat array have been studied, to the best of our knowledge, there is no experimental work or theoretical analysis yet about the nature of electromagnetic interactions between nanotubes or the penetration of electromagnetic waves inside a nanotube. Hence, the mutual inductance between SWCNTs in a bundle merits rigorous investigation before these effects can be included in the inductance model. The only work in the existing literature that attempts to calculate the mutual inductance between the nanotubes of a CNT bundle interconnect assumes a nanotube as a solid metallic conductor with an equivalent conductivity. Since there is no physical justification for the validity of this approach, we refrain from using this model. Neglecting the mutual inductance between CNTs in a bundle will not have a large impact on the performance analysis shown here. Under the assumption that the nanotubes of a bundle are magnetically isolated (no mutual inductance effects), the effective inductance can be treated as the parallel combination of the inductance corresponding to each SWCNT. The inductance of the CNT bundle interconnect is then given by---(9)

3. 2. 3 Simulation Result-

A bundle of 100 SWCNT is taken with the diameter of each CNT being 1 nm. The bundle is considered to be 10 X 10 arrangement giving a square shape to the bundle. Considering a 0. 34 nm gap between each single SWCNT, the width of the bundle comes to around 13. 06 nm. The equivalent circuit for a SWCNT bundle is given in Fig 3. 3. The circuit for SPICE simulation and equivalent parameters was calculated as given in above sections. Fig 3. 3 Equivalent Circuit of SWCNT BundleFig 3. 4 Screen Shot of Simulation of SWCNT Bundle (300µm)For the PSPICE simulation of the circuit, a square wave of 100mv amplitude with Fall time and Rise Time of 0. 1us each , pulse width of 0. 3us and period of 0. 5us is considered. Table 3. 1 consists of Driver and Load parameters for the circuit. ParameterRdrCdrCloadValue18. 33 K Ohms0. 03fF0. 065fFTable 3. 1 Driver and Load Parameters of SWCNT BundleFig 3. 5 Input/Output Waveform of Simulation for SWCNT BundleIn the above simulation figure Input and Output seem to be coinciding but there is a delay in terms of nanoseconds between the two square waveforms. The simulations have been carried out for 100µm, 300µm and 1000µm lengths of interconnect and the delay values have been tabulated in Table3. 2Length of InterconnectDelay of an Isolated SWCNTDelay of 100 SWCNT Bundle100 um2ns0. 0766 ns300 um17. 5 ns0. 3422 ns1000 um0. 186 ns2. 4858 nsTable 3. 2 Delay Comparison of Isolated SWCNT and a Bundle

3. 3 DWCNT Interconnect

We consider that DWCNT bundle is easy to be manufactured in the future. It was demonstrated that large-diameter MWCNT based interconnect also had high performance. However, MWCNT structure is more complex than SWCNT and DWCNT, so it will be harder to set the number of graphene in MWCNT in the process of manufacturing, which decides the performance of MWCNT interconnects. 1) Resistance: A DWCNT is the simplest geometry of an MWCNT. Because of the Van der Waals force, the space between two shells is kept to be a constant of 0. 34 nm. Since the diameter of the internal shell is different from that ofexternal shells in a DWCNT, their corresponding per-unit length resistances are different and denoted by Rint and Rext, respectively. Both of them can be calculated by (10) and (11), when the diameter of DWCNT is smaller than 5 nm. In addition to Rint and Rext, there is a conductance Gt ≈ (10 kΩ)−1/μm between two shells, which is contributed by the tunneling effect . Therefore, the series resistances of a DWCNT bundle is calculated by---(10)---(11)---(12)Where n’CNT is the total number of DWCNTs in the bundle. 2) Capacitance: The per-unit-length capacitance of a DWCNT consists of three parts. a) The electrostatic capacitances between the external shell and the ground plane (CES−b) and between two DWCNT bundles (Cm) are calculated based on the copper wires with the same cross section as previously described. Because the internal shell is shielded by the external one, the electrostatic capacitance between the internal shell and the ground plane can be neglected. b) Since a DWCNT behaves as a metallic coaxial interconnect, the electrostatic coupling capacitance between adjacent shells can be expressed by---(13)c) The quantum capacitance is represented by 4CQ. The per-unit-length capacitance of a DWCNT bundle, together with the electrostatic capacitances, is calculated by---(14)--- (15)3) Circuit Model: Since the per-unit-length inductance of a DWCNT bundle is independent of the diameter of the external shell of DWCNT included, its value is the same as that of the SWCNT bundle. Based on the earlier analysis, an equivalent-circuit model of a DWCNT bundle is built, as shown in Fig. 3. 6Fig 3. 6 Equivalent Circuit of DWCNT BundleFig 3. 7 Screen Shot of Simulation of DWCNT Bundle (100μm)

Simulation-

Here two configurations of DWCNT bundle have been taken, a bundle of 64 DWCNT with the diameter of each inner shell being 1 nm and outer shell being 1. 34 nm. The bundle is considered to be 8 X 8 arrangement to obtain a square shaped bundle. 8 X 8 arrangement is taken with the prime aim to emulate the dimensions of 100 SWCNT bundle taken above so as to get a fair comparison of how an interconnect with a similar dimensions performs in case of SWCNT and DWCNT configurations respectively. In this case the width of the bundle comes to around 13. 1 nm. Then a configuration of 7X7 arrangement is taken in a square shaped bundle again with the width coming around to 11. 42nm. The main idea is to show how DWCNT performs better even with comparatively fewer CNTs with reduced dimensions. The equivalent circuit for a DWCNT bundle is given in Fig 3. 7 The circuit for SPICE simulation and equivalent parameters were calculated for the bundle as given in above sectionFor the SPICE simulations the same square wave, driver and load parameters have been taken just like for the SWCNT bundle. The delay values for both the configurations have been tabulated in Table 3. 3Fig 3. 8 Input/output Waveform of Simulation of DWCNT BundleLength of Interconnect100μm300μm1000μmDelay of 49 DWCNT Bundle0. 0742ns0.

3202ns2. 245nsDelay of 64 DWCNT bundle0. 0700ns0. 3010ns1. 875nsTable 3. 3 Delay values of 49 and 64 DWCNT Bundles

3. 4 Mixed CNT Interconnect

Modelling is an important aspect towards the realisation of CNTs as VLSIinterconnects. MCBs are complex structures that contain both SW and MWCNTs in it. So, modelling of such a bundle is not as easy as modelling of other CNT-based interconnect structures. In addition to intrinsic R, L and C parameters, other extrinsic parameters that depend on the fabrication process, structure and geometry of the interface material, also exists. Hence, it is very important to consider such extrinsic effects while modelling MCB interconnects. First, the role of imperfect metal-nanotube contacts on the conductivity of the interconnect is considered. The resulting effect due to imperfect contacts is the inter-CNT capacitance. This capacitance arises due to the unequal potentials that each CNT has in the bundle. However since we have considered a SWCNT/DWCNT combination for the MCB bundle, inter capacitance need not be considered. However it has to be considered when going for triple walled CNTs. In addition, tunnelling conductance also arises due to the same reason and even its effect is nominal since DWCNT is considered here. The equivalent circuit of a MCB interconnect with realistic parameters is presented. The delay due to the above parameters is calculated and the relative position of the CNTs in the bundle is predicted. A combination of 25 SWCNTs and 25 DWCNTs is taken to arrive at a Mixed CNT bundle. Even here a square shape arrangement is considered. The width and overall dimensions turn out to be small with this 25/25 configuration of

SWCNT and DWCNT respectively. The idea is to show how Mixed CNTs perform better even with smaller dimensions when compared to its SWCNT and DWCNT counterparts. With 50/32 combination of SWCNT and DWCNT respectively, the dimensions come closer to that of 100 SWCNT and 49 DWCNT configurations which have width nearly equal to 13. 1 nm. So the comparison can be drawn from both the configurations. The circuit for SPICE simulation is given in Fig 3. 9 which involves a combination of equivalent circuits of SWCNT bundle and DWCNT bundle and equivalent parameters were calculated individually for SWCNT part and DWCNT part as given in the above sections of SWCNT and DWCNT parameter calculations. Fig 3. 9 Equivalent Circuit of Mixed CNT(SWCNT/DWCNT)Fig 3. 9. 1 Screen Shot of Simulation of Mixed CNT Bundle(50/32-1000µm)Fig 3. 9. 2 Input/Output Waveform of SimulationFor the PSPICE simulation of the circuit, a square wave of 100mv amplitude with Fall time and Rise Time of 0. 1us each, pulse width of 0. 3us and period of 0. 5us is considered. Table 3. 4 consists of Driver and Load parameters for the circuit. ParameterRdrCdrCloadValue18. 33 K Ohms0. 03fF0. 065fFTable 3. 4 Driver and Load Parameters for Mixed CNTThe simulations have been carried out for 100µm, 300µm and 1000µm lengths of interconnect and the delay values have been tabulated in Table 3. 5Length of Interconnect100µm300µm1000µmDelay of 25/25 configuration0. 0691ns0. 2746ns1. 7172nsDelay of 50/32 configuration0. 0650ns0. 2384ns1. 3420nsTable 3. 5 Delay Value of the Two Configurations of Mixed CNT Bundle

3. 5 Analysis of Results

Table 3. 6 gives a glance of all the delaysSingle SWCNTSingle DWCNTBundle of 100 SWCNTBundle of 50 DWCNTBundle of 64 DWCNTMixed25/25Mixed50/32100µm-2ns0. 92ns0. 0766ns0. 0741ns0. 0700ns0. 0691ns0. 0650ns300µm-17. 5ns9ns0. 3422ns0. 3202ns0. 3030ns0. 2746ns0. 2384ns1000µm-0. 187us0. 069us2. 4858ns2. 245ns1. 875ns1. 7172ns1. 342nsTable 3. 6 Delays of all configurations (Length Vs Delay)Fig 3. 9. 3 Length of Interconnect (100µm) Vs DelayFig 3. 9. 4 Length of Interconnect (300µm) Vs DelayFig 3. 9. 5 Length of Interconnect (1000µm) Vs DelayFrom the above figures and tables it is clear that Mixed CNT bundles offer best performance at all interconnect lengths. Also DWCNT bundles performance is better than SWCNT bundle at each of the three interconnect lengths. The performance of Mixed CNT can be attributed to the fact that it utilizes both the factors of density from DWCNTs and Metallic nature of CNTs from SWCNTs.

Chapter 5

CONCLUSION

The present work analyses the mixed CNT bundles as interconnects. It has been observed that the resistance of CNT bundle interconnects can be minimized by also taking the effect of average mean free path and inner to outer diameter ratio. The bundles of CNTs have smaller resistances for Intermediate and Global interconnects. By taking the optimum value of all parameters viz. average mean free path, average diameter, inner to outer diameter ratio and probability of metallic tubes, higher reduction has been achieved in resistance of the bundle than the previously reported research in literature for both intermediate and global interconnects. Therefore, mixed CNT bundle is a promising candidate for Intermediate and Global interconnects for various technology nodes. In conclusion, a comprehensive and realistic evaluation of SWCNT bundle, DWCNT Bundle and Mixed CNT interconnects has shown significant advantages over Cu in terms of performance. The equivalent circuit parameters needed for analysing interconnects delay have been studied in detail, highlighting the underlying assumptions. The correct length-dependent behaviour of the voltage bias-dependent interconnect resistance and the factors influencing CNT interconnect contact resistance have been presented. Circuit development of each configuration has been shown in detail, explaining how the parameters are calculated for each of the circuit. The physical dimensions of the interconnect have been taken into account which gives us a fair comparison between interconnects of same dimensions at various lengths. The outcome of analysis has been that, basically all these CNT configurations are better than the traditional Cu interconnects and out of those CNT bundles, Mixed CNT has a better performance and the reasons for the same has been explained in the above sections. In this project, cross talk performance analysis of parallel SWCNT, Mixed CNT and DWCNT bundle interconnects was carried out. The theoretical analysis is based on some modified equivalent-circuit models of SWCNT, DWCNT and Mixed CNT bundles with inductive and capacitive couplings treated appropriately, by which crosstalk-induced time delay, voltage glitch, etc., can be captured accurately. Line length was taken as 1000µm and results were compared for that length since at that length the apparent effects of interferences and unnecessary glitches effect would be most visible. It is demonstrated that Mixed CNT are equally effected as DWCNT and SWCNT bundle interconnects as they are implemented at intermediate and global levels, respectively, and, in particular, for longer interconnect. Although the suppression on crosstalk-induced glitch using DWCNT and SWCNT bundles is not so effective as compared with that of Cu wires given in literature, both SWCNTs and DWCNTS along with Mixed CNTs are very competitive for future interconnects in the development of advanced high-speed ICs.