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DESIGN AND EFFICIENCY ANALYSIS OF NANOCARBON INTERCONNECT STRUCTURES

Dr. D. Nirmal,
Associate Professor,
Department of Electronics and Communication Engineering, Karunya university,
Coimbatore, Tamil Nadu.
Email id: nirmal@karunya.edu

Abstract: With significant reduction in the size of ICs, there has been a massive increase in the operating speed. Due to this condition, the area available for interconnects within the transistor and between transistors in an IC is greatly reduced. Carbon wires pose high resistance and power dissipation in constrained space. It is necessary to opt efficient means to overcome this issue. The drawbacks of traditional metallic interconnects are overcome by nanocarbon interconnects. Considering factors such as shrinking dimensions, interconnect delay and power dissipation, we have considered four nanocarbon interconnect structures for analysis in this paper. The design and efficiency are analysed for Graphene Nanoribbon (GNR), Carbon Nanotube, Cu-Nanocarbon and All Carbon 3-D interconnects.

Keywords: Nanocarbon Interconnects, Multilayer Graphene, Graphene Nanoribbon, Carbon Nanotube, Cu-Nanocarbon, All Carbon 3-D

1. INTRODUCTION

The reduction in the transistor size has enabled packing more functions into a single IC. The number of transistors on-chip doubles every two years as predicted by Moore's law [1]. This reduction in the transistor size affects the interconnect performance. Traditional metal interconnects does not do well in condensed dimensions [2]. The probability of electrons being scattered also increases thereby affecting the interconnect performance and power dissipation. Copper interconnects are affected by steep increase in resistance [3]. Various research has been done to overcome the drawbacks of the traditional metal interconnects. Several elements such as tungsten have been tested and applied to replace copper. Tungsten FETs served as a better substitute to copper interconnects due to its superior tolerance to electromigration. FinFET and Tunnel-FETs are also used as substitutes for optimising circuit performance [4].

Over the years, several alternative elements such as carbon and graphene are suggested and tested as interconnects and have proved to be more efficient than the old-fashioned metal interconnects. Metal depositions are often used between nanocarbon elements and silicon to overcome high contact resistance [5]. With regard to

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the rapid advancements in the nanocarbon interconnects, we review the design and analysis of these structures. These materials have astonishing properties like extreme thermal conductivity, high current-carrying density and so on [6]. There are several ways in which nanocarbon interconnects can be used in transistors. Few such models are considered for our comparison in this paper.

2. GRAPHENE NANORIBBONS (GNR) INTERCONNECTS

Graphene Nanoribbons are an attractive option for interconnect applications. Multilayer Graphene Nanoribbons (MLGNR) Interconnects are advantageous over single layer Graphene Nanoribbons (SLGNR) due to its lower resistance. MLGNR Interconnects can be grown directly over silicon substrate at a temperature of 300° using diffusion synthesis method or Chemical Vapour Deposition (CVD) method [7].

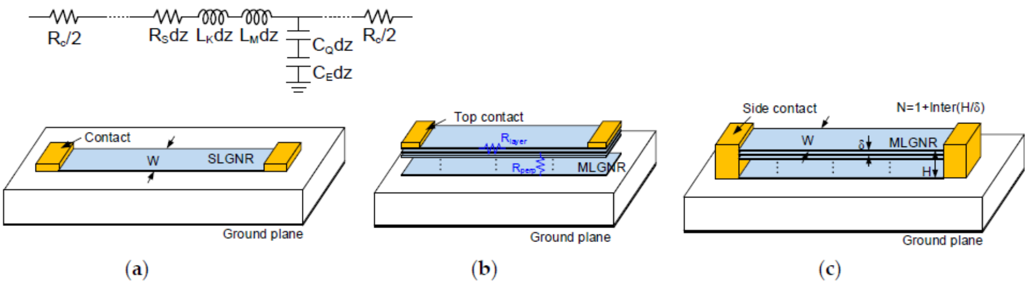

Figure 1. (a) Monolayer GNR (b) Top-contacted MLGNR and (c) Side-contacted MLGNR Interconnects

They are further categorised as top-contact MLGNR (TC-MLGNR) and side-contact MLGNR (SC-MLGNR) [8]. SC-MLGNR offers better performance than TC-MLGNR. In figure 1, we see the schematic representation of different types of GNR. Here, H represents the thickness of interconnect, δ represents van der Waal's gap between neighbouring graphene layers and N is the graphene layers count [9].

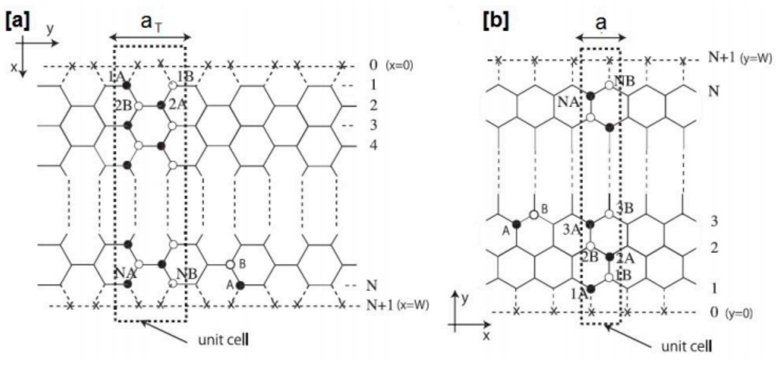

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Figure 2. Graphene Nanoribbon Structure (a) Armchair Ribbon (b) Zigzag Ribbon [10]

Figure 2 shows two basic Graphene Nanoribbon structures in which N represents the dimer count for armchair ribbon and zigzag line count for zigzag ribbon. For armchair ribbon, unit cell length is $a_T = \sqrt{3a}$ and unit cell width is ω= (N+1) a/2. For zigzag ribbon, unit cell length is a and unit cell width is ω (ω= $[\frac{\sqrt{3Na}}{2} + a/\sqrt{3}]$). Several Researchers have analysed MLGNR interconnect structures. The conductance of GNR interconnects can be calculated as a function of Fermi level, chirality, width, and the type of electron scatterings at the edges [11].

Research is been done to improve the electrical contact between CNT vias and graphene lines as well as to reduce the resistance variations in carbon interconnects [12]. [13] Proposes an efficient method to fabricate interconnects using MLG with low resistivity. Doped graphene nanoribbons (DGNR) interconnects are also compatible with CMOS and offer smaller electrical resistivity than typical copper interconnects [14]. An alternative method of manufacturing carbon nanoribbons is to grow graphene and CNT in high temperature on different substrates and then move them to a target substrate to form interconnects structures [15].

3. CARBON NANOTUBE (CNT) INTERCONNECTS

Despite being the strongest material identified, Carbon Nanotubes have several mindboggling advantages. They are better conductors of electricity than copper and better heat transmitters than diamond. A single walled carbon nanotube (SWCNT) is nothing but a single graphite sheet rolled to form a tube. The ends are closed with half of one fullerene molecule. SWCNT can withstand high current density greater than 10^9 A/cm^2 [16]. Multi-walled Carbon Nanotubes (MWCNT) consists of a parallel assembly of coaxial SWCNTs which are separated from each other by Van der Waal's gap. SWCNT and MWCNT are prospective materials that can replace tungsten due to their superior electrical and thermal characteristics [17].

These CNTs can be used in a wide range of applications including electrical, mechanical and electromechanical fields. They are an excellent choice for nanoelectronic components. Further, CNT in combination with polymer in the ratio of 1:2 can also be used as electronic interfaces [18]. Carbon nanotubes and graphene are best suited elements for the manufacture of flexible electronic devices [19]. Doped CNT presents remarkable characteristics and can be used as local interconnects [20]. CNT interconnects are widely classified into monolayer SWCNT, bundled SWCNT and MWCNT as represented in Figure 3.

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Bundled SWCNT make better on-chip vias since they reduce temperature rise and improve electromigration resistance [2]. One-third of shells in MWCNTs are metallic. The conducting channel count of a shell is given by

$$N_{dt} = \begin{cases} 2.04 \text{ X } 10^5 \text{TD} + 0.425, \text{D} > \dfrac{D_T}{\text{T}} \\ \dfrac{2}{3}, D < \dfrac{D_T}{\text{T}} \end{cases}$$

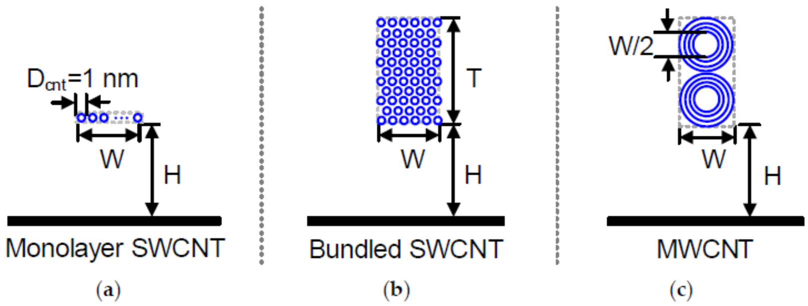

Figure 3 Cross-sectional view of (a) monolayer SWCNT, (b) bundled SWCNT and (c) MWCNT interconnects

Where D_T=1300nm·K. Repeater can be employed to reduce the interconnect delay in high performance devices [21].

4. CU-NANOCARBON INTERCONNECTS

Integrating copper matrix with CNT is rather challenging since there is a notable incompatibility in the surface energy between the two materials [22]. Poor electrical contact at the copper-CNT interface can be improved by the introduction of chromium to bridge CNTs [23]. Further, oxidation of copper can be reduced with the help of passivation by incorporating garaphitic carbon along with the basic carbon structure [24].

Various factors such as effective resistance, delay, energy dissipation, step response, and relative stability are analysed to evaluate the performance of Cu-Nanocarbon Interconnects [25]. The resistance of Cu-CNT is slightly higher than that of bulk Cu. The average energy consumption of each interconnect during switching is calculated using the following formula

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$$E = \frac{1}{2}\,(C_d + C_L + Cl)V_{DD}^2$$

Where V_{DD} represents the supply voltage. Light-weight copper-multiwalled carbon nanotube (Cu-MWCNT) wires can transfer 28% more current than the normal copper interconnects. During the design of electrochemical approaches for integration of Cu-CNT composites, it is essential to closely consider the CNT functionalization, since copper can be affected by the integrity, purity and other factors of CNT [26].

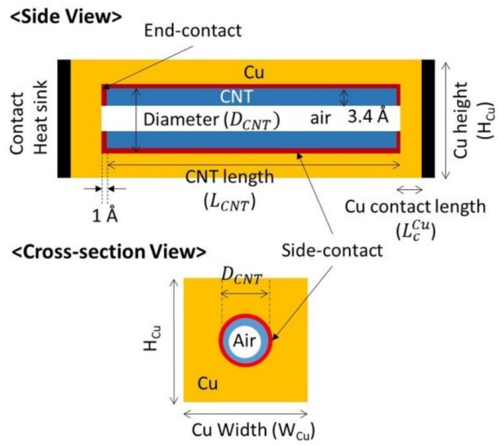

Figure 4 Schematic diagram of Cu-CNT composite interconnects

5. ALL-CARBON 3-D INTERCONNECTS

Integration of multilayer graphene (MLG) wires along with carbon nanotube (CNT) vias, aided by an exclusive carbon-nickel alloy interaction technology is used in creating the all-carbon 3D interconnects. CNT in combination with 3D IC technology is used for vertical interconnects with high via aspect ratio. They can be grown together with CMOS devices during monolithic 3D IC process [27]. If copper interconnects are used in the circuit, it may be necessary to reduce the resistivity of the nanocarbon interconnects to match with that of the copper interconnects. Whereas, this technique helps us in overcoming the problem and elevates the performance without disrupting the device. Through Silicon Via (TSV) based 3D CNT integration is an efficient solution for developing highly packed circuits. The device density is increased and wiring is made compact. TSV improves the hybrid functionality of the chip along with providing immunity to noise signals, increasing the signal propagation speed and power optimization due to the decreased wire length [28].

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The electrothermal characteristics of all-carbon 3-D interconnects discussed in [29] use a Finite Element Method (FEM) algorithm. It overcomes inconsistent temperature distribution and provides a good heat dissipation capability as CNT vias are placed below the heat sink. The monolithic 3-D assimilation provides highly fine-grained combination of logic circuits for substantial amount of memory [30].

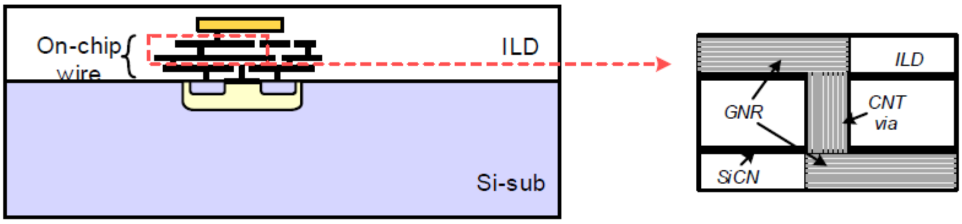

Figure 5 All-carbon 3-D interconnect

6. CONCLUSION

In this paper, we have analysed the performance and efficiency of various nanocarbon interconnects. These interconnects prove to be advantageous over the traditional carbon wires. Carbon wires offer high resistance as transistors are scaled. Whereas, nanocarbon interconnects overcomes the issues of electromigration resistance, interconnect delay and power dissipation. Pure nanocarbon interconnects impose fabrication limits. However, they offer better solutions than Cu-nanocarbon interconnects. An ideal solution to overcome most of the interconnect issues would be to use both of these interconnects in combination.

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