DESIGN AND EFFICIENCY ANALYSIS OF NANOCARBON INTERCONNECT STRUCTURES

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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
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](image)

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].

![Graphical representation of different types of GNR](image)
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 $a_T = \sqrt{3}a$ and unit cell width is $\omega = (N+1) a/2$. For zigzag ribbon, unit cell length is $a$ and unit cell width is $\omega = \left(\frac{\sqrt{3}N^2}{2} + \frac{a}{\sqrt{3}}\right)$. 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.
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

$$N_{dc} = \begin{cases} 
2.04 \times 10^5 \text{TD} + 0.425, & D > \frac{D_T}{T} \\
\frac{2}{3}D < \frac{D_T}{T} 
\end{cases}$$

Where $D_T = 1300\text{nm-K}$. 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 graphitic 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
\[ E = \frac{1}{2} (C_a + C_L + C_l) V_{DD}^2 \]

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].
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.

References

[1] Moore, Gordon E. "Cramming more components onto integrated circuits." (1965): 114-117.

[2] Zhao, Wen-Sheng, Kai Fu, Da-Wei Wang, Meng Li, Gaofeng Wang, and Wen-Yan Yin. "Mini-Review: Modeling and Performance Analysis of Nanocarbon Interconnects." Applied Sciences 9, no. 11 (2019): 2174.
[3] Yang, Cary Y. "All-Carbon Interconnects-from 1D to 3D." In Meeting Abstracts, no. 10, pp. 898-898. The Electrochemical Society, 2018.

[4] Prasad, D., and A. Naeeemi. "Interconnect Design and Technology Optimization for Conventional and Emerging Nanoscale Devices: A Physical Design Perspective." In 2018 IEEE International Electron Devices Meeting (IEDM), pp. 5-1. IEEE, 2018.

[5] Abe, Yusuke, Anshul Vyas, Richard Senegor, Patrick Willhite, and Cary Y. Yang. "Contact engineering for nanocarbon interconnects." In 2015 IEEE 15th International Conference on Nanotechnology (IEEE-NANO), pp. 1194-1196. IEEE, 2015.

[6] Sato, Shintaro, Daiyu Kondo, Shinichi Hirose, and Junichi Yamaguchi. "Nanocarbon Technology for Development of Innovative Devices." FUJITSU Sci. Tech. J 53, no. 2 (2017): 23-30.

[7] Sato, Shintaro. "Nanocarbon interconnects: Current status and prospects." In 2016 International Conference on Electronics Packaging (ICEP), pp. 66-69. IEEE, 2016.

[8] Kumar, Vachan, Shaloo Rakheja, and Azad Naeeemi. "Performance and energy-per-bit modeling of multilayer graphene nanoribbon conductors." IEEE transactions on electron devices 59, no. 10 (2012): 2753-2761.

[9] Agrawal, Yash, Mekala Girish Kumar, and Rajeevan Chandel. "A novel unified model for copper and MLGNR interconnects using voltage-and current-mode signaling schemes." IEEE transactions on electromagnetic compatibility 59, no. 1 (2016): 217-227.

[10] Wakabayashi, K.; Dutta, S. “Nanoscale and edge effect on electronic properties of graphene.” Solid State Commun. (2012), 152, 1420–1430.

[11] Naeeemi, Azad, and James D. Meindl. "Conductance modeling for graphene nanoribbon (GNR) interconnects." IEEE electron device letters 28, no. 5 (2007): 428-431.

[12] Ramos, R., A. Fournier, M. Fayolle, J. Dijon, C. P. Murray, and J. McKenna. "Nanocarbon interconnects combining vertical CNT interconnects and horizontal graphene lines." In 2016 IEEE International Interconnect Technology Conference/Advanced Metallization Conference (IITC/AMC), pp. 48-50. IEEE, 2016.
[13] Sato, Shintaro. "Nanocarbon interconnects: Demonstration of properties better than Cu and remaining issues." In 2015 IEEE International Interconnect Technology Conference and 2015 IEEE Materials for Advanced Metallization Conference (IITC/MAM), pp. 313-316. IEEE, 2015.

[14] Jiang, Junkai, Jae Hwan Chu, and Kaustav Banerjee. "CMOS-compatible doped-multilayer-graphene interconnects for next-generation VLSI." In 2018 IEEE International Electron Devices Meeting (IEDM), pp. 34-5. IEEE, 2018.

[15] Votzke, Callen, Uranbileg Daalkhaijav, Yiğit Mengüç, and Matthew L. Johnston. "3D-Printed Liquid Metal Interconnects for Stretchable Electronics." IEEE Sensors Journal 19, no. 10 (2019): 3832-3840.

[16] Sharma, Rohit, and Atul Kumar Nishad. "Performance Evaluation of AsF5-intercalated Top-Contact Multilayer Graphene Nanoribbons for Deeply Scaled Interconnects." High-Speed and Lower Power Technologies: Electronics and Photonics (2018).

[17] Vyas, Anshul A., Changjian Zhou, Patrick Wilhite, Phillip Wang, and Cary Y. Yang. "Nanocarbon via interconnects." In 2016 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), pp. 5-12. IEEE, 2016.

[18] Nirmalraj, Peter, Maria Cristina dos Santos, Jorge Mario Salazar Rios, Diana Davila, Fiorella Vargas, Ullrich Scherf, and Maria Antonietta Loi. "Polymer–Nanocarbon Topological and Electronic Interface." Langmuir 34, no. 21 (2018): 6225-6230.

[19] Yogeswaran, Nivasan. "Graphene field effect transistor based pressure sensors for tactile sensing applications." PhD diss., University of Glasgow, 2019.

[20] Todri-Sanial, Aida, Raphael Ramos, Hanako Okuno, Jean Dijon, Abitha Dhavamani, Marcus Widlicenus, Katharina Lilienthal et al. "A survey of carbon nanotube interconnects for energy efficient integrated circuits." IEEE Circuits and Systems Magazine 17, no. 2 (2017): 47-62.

[21] Zhao, Wen-Sheng, and Wen-Yan Yin. "Comparative study on multilayer graphene nanoribbon (MLGNR) interconnects." IEEE Transactions on Electromagnetic Compatibility 56, no. 3 (2014): 638-645.
[22] Sundaram, Rajyashree, Takeo Yamada, Kenji Hata, and Atsuko Sekiguchi. "Electrical performance of lightweight CNT-Cu composite wires impacted by surface and internal Cu spatial distribution." Scientific reports 7, no. 1 (2017): 9267.

[23] Wright, Kourtney, and Andrew Barron. "Catalyst residue and oxygen species inhibition of the formation of hexahaptometal complexes of group 6 metals on single-walled carbon nanotubes." C 3, no. 2 (2017): 17.

[24] Isaacs, Romaine A., HM Iftekhar Jaim, Daniel P. Cole, Karen Gaskell, Oded Rabin, and Lourdes G. Salamanca-Riba. "Synthesis and characterization of copper-nanocarbon films with enhanced stability." Carbon 122 (2017): 336-343.

[25] Cheng, Zi-Han, Wen-Sheng Zhao, Linxi Dong, Jing Wang, Peng Zhao, Haijun Gao, and Gao Feng Wang. "Investigation of copper–carbon nanotube composites as global VLSI interconnects." IEEE Transactions on Nanotechnology 16, no. 6 (2017): 891-900.

[26] Kazimierska, Ewa, Enrico Andreoli, and Andrew R. Barron. "Understanding the effect of carbon nanotube functionalization on copper electrodeposition." Journal of Applied Electrochemistry (2019): 1-11.

[27] Vollebregt, Sten, and Ryoichi Ishihara. "The direct growth of carbon nanotubes as vertical interconnects in 3D integrated circuits." Carbon 96 (2016): 332-338.

[28] Rao, Madhav. "Electrical modeling of copper/carbon nanotubes for 3d integration." In 2016 IEEE 16th International Conference on Nanotechnology (IEEE-NANO), pp. 763-766. IEEE, 2016.

[29] Li, Na, Junfa Mao, Wen-Sheng Zhao, Min Tang, Wenchao Chen, and Wen-Yan Yin. "Electrothermal cosimulation of 3-D carbon-based heterogeneous interconnects." IEEE Transactions on Components, Packaging and Manufacturing Technology 6, no. 4 (2016): 518-526.

[30] Shulaker, Max Marcel, Hai Wei, Subhasish Mitra, and H-S. Philip Wong. "Carbon Nanotubes for Monolithic 3D ICs." In Carbon Nanotubes for Interconnects, pp. 315-333. Springer, Cham, 2017.

[31] Dąbrowska, Agnieszka. "Nanocarbon/epoxy composites: Preparation, properties, and applications." In Nanocarbon and its Composites, pp. 421-448. Woodhead Publishing, 2019.
[32] Vargas-Bernal, Rafael, Gabriel Herrera-Pérez, and Margarita Tecpoyotl-Torres. "The Impact of Carbon Nanotubes and Graphene on Electronics Industry." In Advanced Methodologies and Technologies in Digital Marketing and Entrepreneurship, pp. 382-394. IGI Global, 2019.

[33] Jiang, Junkai, Jiahao Kang, Jae Hwan Chu, and Kaustav Banerjee. "All-carbon interconnect scheme integrating graphene-wires and carbon-nanotube-vias." In 2017 IEEE International Electron Devices Meeting (IEDM), pp. 14-3. IEEE, 2017.

[34] Zhao, Wen-Sheng, and Wen-Yan Yin. "Comparative study on multilayer graphene nanoribbon (MLGNR) interconnects." IEEE Transactions on Electromagnetic Compatibility 56, no. 3 (2014): 638-645.

[35] Liang, Feng, Gaofeng Wang, and Wen Ding. "Estimation of time delay and repeater insertion in multiwall carbon nanotube interconnects." IEEE Transactions on Electron Devices 58, no. 8 (2011): 2712-2720.

[36] Shunin, Yu, S. Bellucci, Yu Zhukovskii, V. Gopeyenko, N. Burlutskaya, and T. Lobanova-Shunina. "Nanocarbon electromagnetics in CNT-, GNR- and aerogel-based nanodevices: models and simulations." gen 1, no. 1 (2015): 1.

[37] Vyas, Anshul A., Changjian Zhou, Patrick Wilhite, Phillip Wang, and Cary Y. Yang. "Electrical properties of carbon nanotube via interconnects for 30 nm linewidth and beyond." Microelectronics reliability 61 (2016): 35-42.

[38] Vyas, Anshul A. "Carbon Nanotube Interconnects for End-of-Roadmap Semiconductor Technology Nodes." (2016).

[39] Sato, Shintaro. "One and two dimensional nanocarbon materials for innovative functional devices." In 2017 Symposium on VLSI Technology, pp. T46-T47. IEEE, 2017.

[40] Zhao, Wen-Sheng, Gaofeng Wang, Jun Hu, Lingling Sun, and Hui Hong. "Performance and stability analysis of monolayer single-walled carbon nanotube interconnects." International Journal of Numerical Modelling: Electronic Networks, Devices and Fields 28, no. 4 (2015): 456-464.
[41] Lee, Jaehyun, Jie Liang, Salvatore M. Amoroso, Toufik Sadi, Liping Wang, Flamen Asenov, Andrew Pender et al. "Atoms-to-circuits simulation investigation of CNT interconnects for next generation CMOS technology." In 2017 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), pp. 153-156. IEEE, 2017.

[42] Majumder, Manoj Kumar, Jainender Kumar, and Brajesh Kumar Kaushik. "Process-induced delay variation in SWCNT, MWCNT, and mixed CNT interconnects." IETE Journal of Research 61, no. 5 (2015): 533-540.

[43] Jaehyun, Lee, Sadi Toufik, Jie Liang, Vihar Georgiev, Aida Todri-Saniel, and Asenov Asen. "A hierarchical model for CNT and Cu-CNT composite interconnects: from density functional theory to circuit-level simulations." 2017.

[44] Lee, Jaehyun, Salim Berrada, Fikru Adamu-Lema, Nicole Nagy, Vihar P. Georgiev, Toufik Sadi, Jie Liang et al. "Understanding electromigration in Cu-CNT composite interconnects: A multiscale electrothermal simulation study." IEEE Transactions on Electron Devices 65, no. 9 (2018): 3884-3892.

[45] Murugeswari, P., A. P. Kabilan, and V. E. Jayanthi. "Effect of Current Mode Signaling in Carbon Nanotube On-Chip Interconnect." In Journal of Nano Research, vol. 45, pp. 42-48. Trans Tech Publications, 2017.

[46] Mishra, Abhishek, and Mayank Shrivastava. "Unique current conduction mechanism through multi wall CNT interconnects under ESD conditions." In 2016 38th Electrical Overstress/Electrostatic Discharge Symposium (EOS/ESD), pp. 1-6. IEEE, 2016.

[47] Li, Suwen, Salahuddin Raju, Changjian Zhou, and Mansun Chan. "Carbon nanotube contact plug on silicide for CMOS compatible interconnect." IEEE Electron Device Letters 37, no. 6 (2016): 793-796.

[48] Kaushik, Brajesh Kumar, and Manoj Kumar Majumder. "Modeling of Carbon Nanotube Interconnects." In Carbon Nanotube Based VLSI Interconnects, pp. 39-56. Springer, New Delhi, 2015.

[49] Todri-Saniel, Aida, Alessandro Magnani, Massimiliano De Magistris, and Antonio Maffucci. "Present and future prospects of carbon nanotube interconnects for energy efficient integrated circuits." In 2016 17th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), pp. 1-5. IEEE, 2016.
[50] Kreupl, Franz, Andrew P. Graham, G. S. Duesberg, W. Steinhögl, M. Liebau, Eugen Unger, and W. Hönlein. "Carbon nanotubes in interconnect applications." Microelectronic Engineering 64, no. 1-4 (2002): 399-408.

[51] Srivastava, Navin, Rajiv V. Joshi, and Kaustav Banerjee. "Carbon nanotube interconnects: implications for performance, power dissipation and thermal management." In IEEE International Electron Devices Meeting, 2005. IEDM Technical Digest. pp. 249-252. IEEE, 2005.

[52] Srivastava, Navin, and Kaustav Banerjee. "Performance analysis of carbon nanotube interconnects for VLSI applications." In Proceedings of the 2005 IEEE/ACM International conference on Computer-aided design, pp. 383-390. IEEE Computer Society, 2005.

[53] Banerjee, Kaustav, Hong Li, and Navin Srivastava. "Current status and future perspectives of carbon nanotube interconnects." In 2008 8th IEEE Conference on Nanotechnology, pp. 432-436. IEEE, 2008.