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Enhanced thermal management in 3D integrated circuits coupling

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ABSTRACT

3D IC integration, which comprises vertically stacking several IC layers, is one of the new technologies that works well with complementary metal-oxide-semiconductor (CMOS) implementations. The layers of a three-dimensional integrated circuit (3D IC) are physically and electrically connected via copper-silicon bonding and through silicon vias (TSVs). Limitations in 3D IC designs, such as layer-to-layer thermal difficulties and TSV-to-substrate and TSV-to-TSV noise coupling, significantly impact system performance as a whole. Integrating 3D ICs relies heavily on heat spreaders and thermal through silicon vias (TTSVs). Overheating is a common cause of IC failure; however, heat spreaders and FIN to TTSV have been suggested as potential remedies for this problem in the last few years. A 3D IC might melt under the stress of an applied voltage because it becomes hotter inside. Engineers have added fins to the TTSV in a number of ways, each of which maximizes heat dissipation in a different way, in order to reduce this danger. The exceptional thermal cooling characteristics of graphene and carbon nanotubes (CNTs) have led to their widespread dissemination. This research shows that a FIN may efficiently transport thermal energy to a heat sink by using heat spreaders and optimum orientations to distribute heat in all directions. Additionally, we demonstrated the many scenarios in which the IC's potential distribution is impacted by various thermal cooling effects. We found that when it comes to transferring heat away from heat sources and TSVs, CNTs outperform Graphene. We included Al2o3, Si3N4, and SiO2 as examples to examine the consequences of modifying the model's dielectric characteristics.

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1. INTRODUCTION

Since the transistor is the primary building block of electronics, metal-oxide-semiconductor field-effect transistors (MOSFETs) play a crucial role in the IoT. One method for developing compact electronic goods is MOSFET scaling, which is described by Moore's law for contemporary technology.

Since the integrated circuits (IC) is flat, increasing the size of the transistor to save manufacturing space necessitates more metal layers. Wire delays and wire density both increase due to the presence of these metal layers [1]–[5]. Manufacturing ICs becomes more difficult when parasitic capacitance rises due to the increased wire density. Parasitic capacitance dominates and causes delays in interconnects. The connection latency became an issue with the transistor delay. As scalability increases, however, the issue of connection latency becomes more pressing [6], [7]. Concern about the need to decrease connection latency arose inside the IC. An alternate technique that has shown promise is the three-dimensional IC (3D IC). The IC is studied in all three dimensions. Current conspirator there is a trade-off in terms of system performance when using two-dimensional ICs (2D IC) because of their lower device packing densities [8]–[10]. The 3D IC has replaced the two-dimensional IC (2D IC) as the state-of-the-art technology due to its increased signal bandwidth and ability to host millions of devices. In addition, the advent of 3D IC technology and heterogeneous integration has made production for the semiconductor industry more easier. The thermal resistance measures how much heat is lost from the chip's circuit junction to its outside. By cooling the semiconductor, thermal flow limits thermal resistance. The thermal resistance of a chip increases with the number of layers it has. Due to the small size of the devices used in 3D IC, cross-couplings form between the various components in the layer [11], [12]. Cross-talk is another name for cross-coupling. When there is less space between the layers, communication between them improves. This is a major problem with the 3D IC design. Additionally, ICs suffer from the issue of vertical cross-talk. An IC may have cross-talk between its active layers. Layer stacking on a high-quality semiconductor is damaging to the manufacturing method [13]. Getting rid of or making good use of interference is the first step in fixing 3D IC's main issue. To solve this issue, several different circuits will be constructed. The main restrictions of 3D technology are noise coupling and thermal issues. Noise coupling is the connection between the use of high-performance materials for thermal management in 3D IC design, including silicon nitride (Si3N4), aluminium oxide (Al2O3), and silicon dioxide (SiO2).

2. MODEL DESCRIPTION USING TSV

Because of the weak electrical communication between through silicon vias (TSVs) and Si substrate, which causes noisy coupling disturbances between aggressive and victim TVs and between active devices and Si substrate, this 3D IC integration is primarily motivated by this issue [14]–[18]. The problem of noise coupling between TSVs and the Si substrate may be solved by using the right technique. This TSV-based 3D IC suffers from the same noise coupling and heat problems as its 2D counterpart. ETSV, which is nothing more than electrical through silicon-via, experiences noise coupling as a consequence of insufficient electrical signaling, while thermal TSV (TTSV), which is nothing more than thermal via silicon-via, experiences heat as a result of increasing heat. 3DICs have a higher applied potential [17], [18]. With this work, we propose a solution to the stated problem, which is that the effect of heat on an IC varies depending on the direction in which the heat travels [19]–[25]. For instance, if heat is transferred from the heat source to the heat sink in a single direction, the IC may be damaged.

Figure 1 shows the thermal management efficiency of a two-stacked structure, which is analyzed using fins and spreaders with carbon nanotubes (CNT) and Graphene as test materials. The impact on signal integrity and heat dissipation from a 1μW hotspot (1μm × 1μm × 0.5μm) is also evaluated. In this article, I'll explain how traditional 3D IC architecture and graphene-based FIN heat spreaders work together to provide an optimal heat-management solution. To further address the issue of the IC's TTSV without FIN and with a heat spreader (graphene and CNT), we turn the fin towards the heat source and the fin towards the cylinder. This demonstrates how heat impacts in different directions. Table 1 indicates the Suggested material for Fin and Spreaders for effective thermal management. Figure 2 shows simulated proposed structure.

Thermal management system diagram 2 uses fins and TSVs to dissipate heat. Fins transfer heat to the TSV for effective thermal control. Heat is directed away from the power source to prevent local overheating. Figure 3 illustrates the power source, thermal, and ground TSVs' organized positioning. The layout is critical for heat dissipation and electrical communication. TSV placement optimizes thermal channels for optimum performance. CNT A power supply linked to TSVs and a thermal TSV with an extra element to increase heat dissipation is shown in Figure 4. This structural component stabilizes system temperature. The design balances heat dissipation and electrical functioning. Proper heat dispersion improves setup reliability and efficiency. TSVs and other thermal structures optimize system performance and avoid thermal bottlenecks. Table 2 provides ITRS roadmap TSV dimensions.

By directing the fin's heat spreader layer in the opposite direction of the TTSV, performance is enhanced. The TTSV-containing and -free simulated reference structures were compared. The enhanced heat transfer performance provided by a 3D layer structure using TTSV is clearly seen in Figure 5. When it comes to thermal management of a 3DIC, CNTs are superior to graphene (Graphene) when using a FIN path with a cylinder. Heat which is transmitted from a potential source in the direction of the source has better thermal

management than heat which is transmitted towards the cylinder, which has worse thermal management, and this is illustrated in Figure 6.

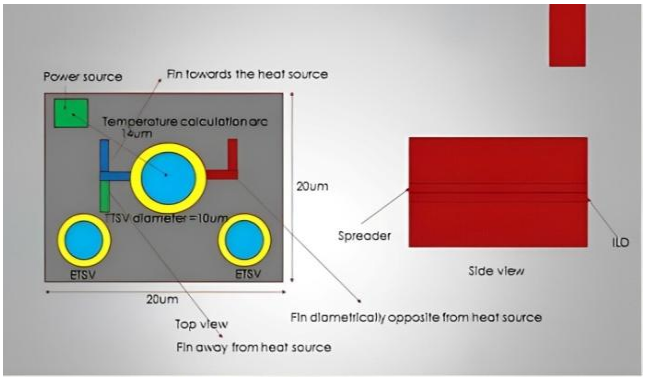

Figure 1. Proposed technique of FIN in various directions

Table 1. Suggested material for Fin and spreaders for effective thermal management

	CNT	GRAPHENE
Thermal conductivity	6600 (w/mk)	2600 (w/mK)
Density	1300 kg/m3	1800 kg/m3

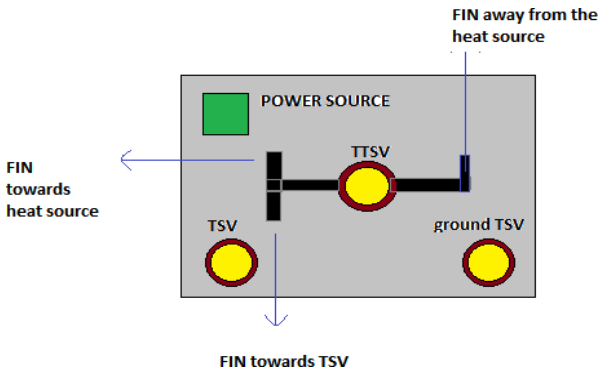

Figure 2. Simulated proposed structure

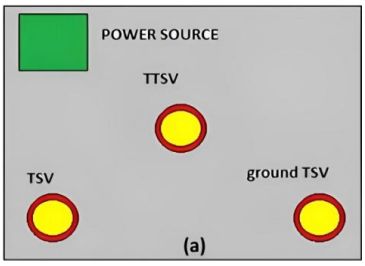

Figure 3. Simulated structure of TTSV without FIN

Table 2. Dimensions of TSV as per ITRS roadmap

Outer Diameter of TSV	1 µm
Outer diameter of TTSV	1 µm
Width and length of silicon substrate	10 µm
Depth of FIN	Variable
Height of silicon substrate	10 µm

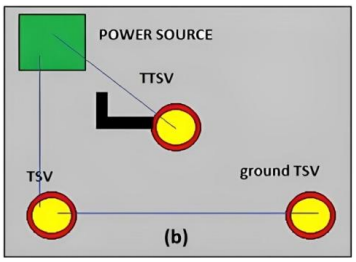

Figure 4. Simulated structure of TTSV with FIN

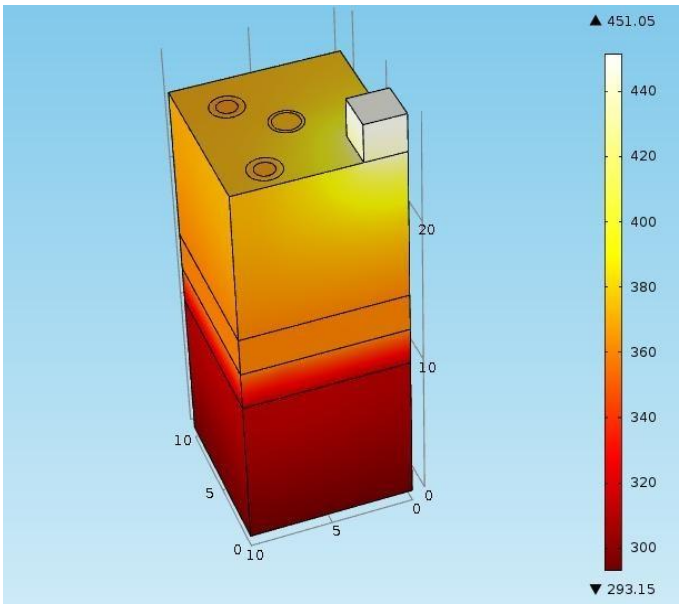

Figure 5. Simulated architecture TTSV without FIN

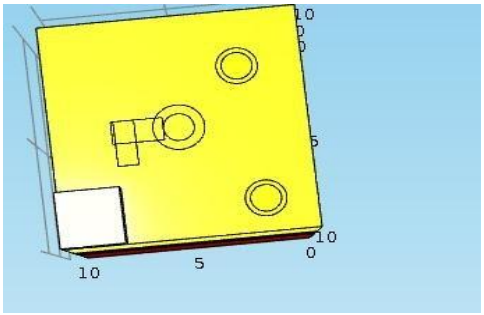

Figure 6. Simulated architecture TTSV with FIN towards heat source

3. RESULTS AND DISCUSSIONS

Compare the thermal cooling effects of CNT-constructed FIN and TSV, and show that the former is better. Due of CNT's ability to reduce heat, FIN's temperature seldom changes. The dramatic temperature changes seen in TSV (Figure 7) lead it to produce greater overall heat production compared to FIN with CNT. ICs are rendered useless due to their excessive heat absorption. The risk of IC failure is reduced since it produces less heat. Figure 8 shows the variations in FIN and TSV temperatures. Since graphene, the FIN, has poor thermal conductivity, the temperature variations are comparable to TSV. Like the TSV, the Graphene FIN absorbs heat from an external source. Figure 9 shows the temperature changes of a CNT-built TSV and FIN power supply. The rapid heat conduction of CNT material makes the power source to FIN cool faster than TSV. The power source to TSV settles near temperature, and the FIN to power supply FIN is CNT.

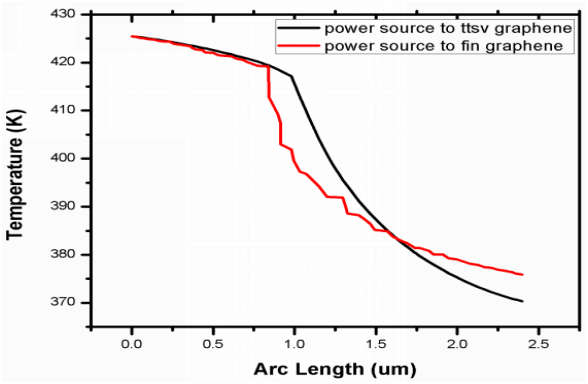

Figure 7. FIN with CNT FIN towards heat source

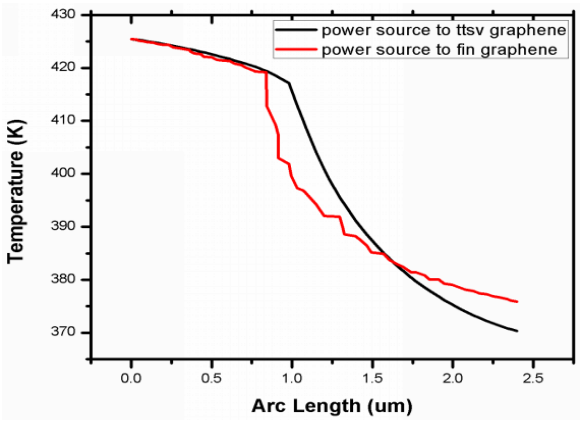

Figure 8. Graphene FIN facing the heat source

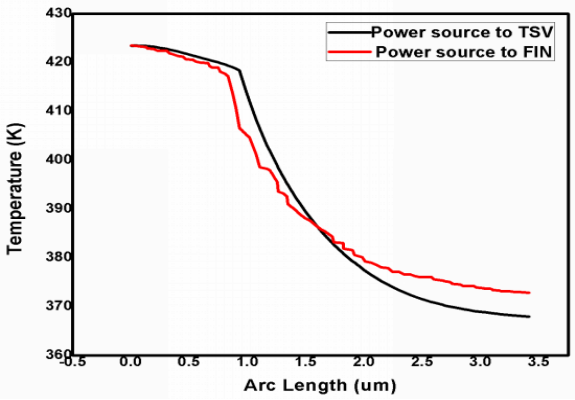

Figure 9. CNT-based FIN with a TSV-leaning orientation

Figure 10 demonstrates temperature change with Graphene-based FIN and TSV power sources. The accompanying chart shows that power source temperature varies similarly for TSV and FIN. The limited heat conductivity of Graphene causes this. Figure 11 illustrates the thermal behavior of through-silicon vias (TSVs) under specific conditions. It highlights temperature variations across different regions, showing thermal gradients and potential hotspots. The results help in understanding heat dissipation efficiency in TSV structures. Figure 12 presents a comparative analysis of thermal performance in different TSV configurations. It demonstrates how design modifications impact temperature distribution and overall thermal management. The insights assist in optimizing TSV structures for improved thermal reliability.

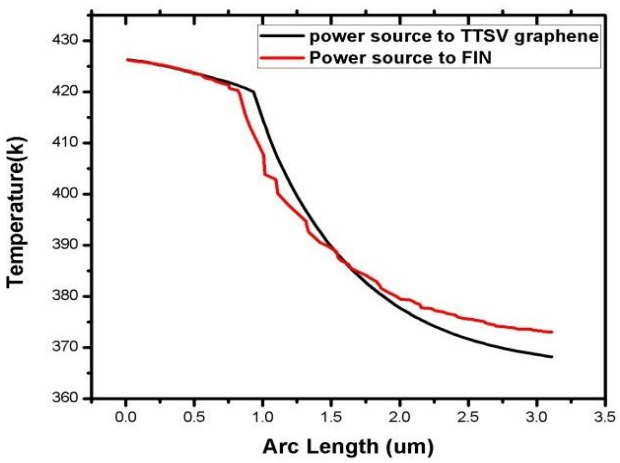

Figure 10. Graphene-based FIN facing TSV

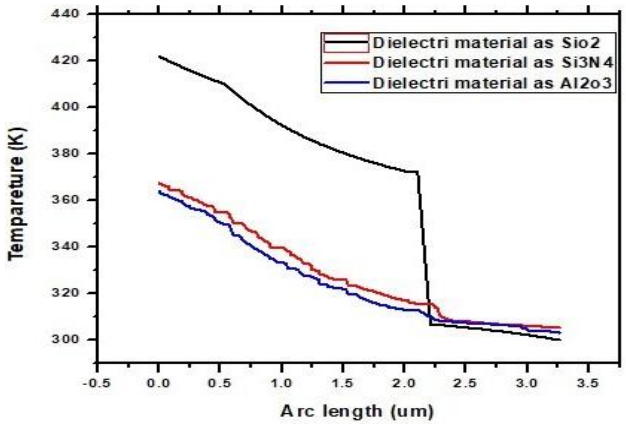

Figure 11. Comparison of Al2o3, Sio2, Si3n4

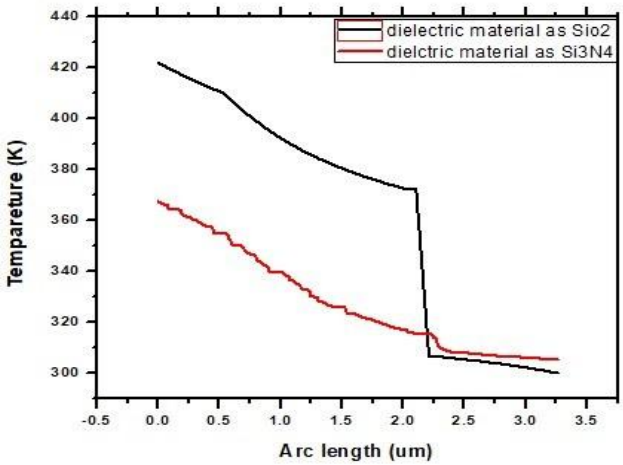

Figure 12. Comparison of Sio2, Si3n4

4. CONCLUSION

The interaction between CNT and graphene and FIN is significantly influenced by the temperature. When compared to the thermal cooling impact of FIN paired with graphene, the effect of FIN mixed with CNTs offers higher performance. FIN made of CNT and directed towards heat source enhances the IC's

temperature resistance and provides better results than FIN made of CNT and orientated towards TSV, and in the examination of the three distinct materials al2o3, si3n4, and sio2, FIN constructed of CNT and orientated towards heat source yields better results than FIN made of CNT and orientated towards TSV. The ability of Si3n4 to block heat transfer is much higher than that of either Al2o3 or Sio2.

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Sadhu Radha Krishna			✓		✓					✓				
Murkur Rajesh	✓					✓				✓				
Malagonda Siva Kumar	✓	✓	✓	✓	✓	✓		✓		✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing -**O**riginal Draft
E : Writing - Review &**E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest regarding the publication of this paper.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee; or: The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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