Electrothermal Study of Cu-CNT Composite TSV using COMSOL Multiphysics®

K. Sable[1], B. Kumari, M. Sahoo
[1]E.mail: sablekomal95@gmail.com
Department of Electronics Engineering, IIT(ISM), Dhanbad-826004, India.

I. Introduction

Although 3D ICs provide several advantages in terms of footprint, speed and power requirement, issues like thermal management should also be taken into consideration. These multi-layer stacked ICs use a through-silicon via (TSV) to connect two interconnect layers, that not only promote signal transfer but also help in heat distribution throughout the structure. A copper-copper combination of interconnect and TSVs is used in 3D ICs. However, certain limitation of copper are encountered at nano-regime, these include problems like electromigration, grain-boundary scattering and surface-roughness scattering [1]. Also due to low thermal conductivity of copper, heat gets trapped within the layers.

Carbon-based material like carbon-nanotubes (CNT) and graphene nano-ribbon (GNR) are thought of as a potential solution to interconnect and TSV material. Due to their high thermal conductivity they help the heat to flow through various layers avoiding the generation of hotspots [2]. In case of electrical conductivity also CNT provides advantages over copper if used in the nanometer regime, as CNTs have high electrical conductivity in nanoscale. Incorporating CNT in copper is practiced when used as a TSV to improve its thermal and electrical conductivity.

Due to the extraordinary physical properties and ease of fabrication, horizontal multi-layered GNR is considered as a interconnect material. In this paper we present electrothermal simulation using Cu, CNT and Cu-CNT as a TSV material and provide a comparative study on the thermal aspects of the TSV material that are used along with multi-layered GNR as an interconnect. Also, we can observe how the proportion of CNT in the composite affects the thermal conductivity.

This paper is organised as follows. Section II demonstrates the experimental setup of the structure. Section III provides model description and use of simulation physics applied to the structure. Section IV contains the results and comparative study of all the three material used as TSV i.e. copper, CNT and a copper-CNT composite. Finally conclusion is drawn in Section V.

II. Experimental Set-up

A TSV 20µm long with a radius of 1µm is sandwiched between two interconnect layers as shown in figure 1. The length, width and thickness of the interconnect is 10µm, 2µm and 0.5µm respectively. The temperature of the top surface is assumed to be 373K (90°C) corresponding to maximum current density that is applied to one edge of the interconnect resembling the current flow through the interconnect. The thermal conductivity and electrical resistivity of CNT and GNR are listed in Table 1 [3]. The same structure is analysed for three different material i.e. Cu, CNT and Cu-CNT composite and the temperature variation along the TSV is compared. To study the effect of change in the proportion of CNT in the Cu-CNT composite the material properties are varied and results are compared. Here, 0.3% and 0.7% of CNT in the Cu-CNT composite is considered for analysis purpose.

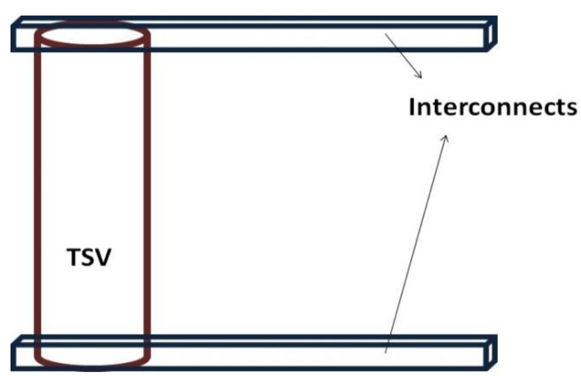


Figure 1. Two interconnect layers connected by a TSV

Table 1. COMSOL material properties [3]

Electrical Resistivity	
Carbon Nanotubes	$6.17\text{x}10^8$ Ω-m
Graphene Nanoribbon	$1.1\text{x}10^8$ Ω-m
Thermal Conductivity	
Carbon Nanotubes	1750 W/(m.K)
Graphene Nanoribbon	700 W/(m.K)

III. Model Description

The electrical and thermal models for copper, CNT and Cu-CNT composite can be individually described below.

A. Copper TSV

The analytical expression for dc resistance is given by,

$$R_{TSV} = \frac{\rho H}{\pi R_{TSV}^2} \quad (1)$$

where ρ is the resistivity of the conducting material. H and R_{TSV} represent the length and radius of the TSV, respectively. For high-frequency signals, however, the increase in resistance due to skin effect should be accounted. The resistance increase due to skin effect is quite significant for higher diameter TSV structures. As for the thermal resistance we adopt a simple model given in [4],

$$R_{TH} = \frac{1}{k_{Cu}} \frac{H}{\pi R_{TSV}{}^2} \quad (2)$$

where, k_{Cu} is the thermal conductivity of copper.

B. CNT TSV

For single-walled CNT, the impedance of the whole CNT bundle is given by,

$$Z_{CNT} = \frac{Z_{SWCNT}}{N_{CNT} F_M} \quad (3)$$

where, Z_{SWCNT} is the impedance of a single-CNT, N_{CNT} is the number of CNTs within the bundle and F_M is the fraction of metallic CNTs. Z_{CNT} is given below as explained in [5],

$$Z_{SWCNT} = \frac{h}{2q^2}\left(1 + \frac{H}{\lambda} + j\omega \frac{H}{2\, v_f}\right) \quad (4)$$

$$N_{CNT} = \frac{2\,\pi\, R_{TSV}^2}{\sqrt{3}\,(d+\delta)^2} \quad (5)$$

here, h is the Planck constant, q is the electron charge, R_{TSV} is the radius of TSV, H is the TSV height, v_f is the fermi velocity ($8\text{x}10^5$m/s), and λ is the mean-free path of the electrons ($\lambda \approx 1\mu m$), d is the distance between two CNTs and δ is the Van der Waal gap[5]. The conductivity of CNT can then be obtained by using the standard model $R = \rho . L/A$.

The thermal conductivity of a CNT bundle is given by,

$$K_{bundle} = K_{CNT} N_{CNT} \left(\frac{r}{R_{TSV}}\right)^2 \quad (6)$$

where K_{CNT} is the thermal conductivity of isolated CNT and r is the radius of a nanotube.

C. Cu-CNT Composite TSV

Cu-CNT TSV has an advantage of fabricational compatibility over CNT for near future applications. It can be fabricated by co-depositing Cu with CNT. From [6], the ratio of the CNT to the total area of TSV is termed as the CNT filling ratio and is given as below,

$$f_{CNT} = \frac{N_{CNT}(D_{CNT}+0.31nm)^2}{4\, R_{TSV}^2} \quad (7)$$

A separation of 0.155nm is assumed between the CNT and copper in the composite. Based on the CNT filling ratio, the electrical conductivity of the composite can be given as below,

$$\sigma_{eff} = (1 - f_{CNT})\,\sigma_{cu} + f_{CNT}\,\sigma_{CNT} \quad (8)$$

where σ_{cu} is the conductivity of copper and σ_{CNT} is the conductivity of CNT.

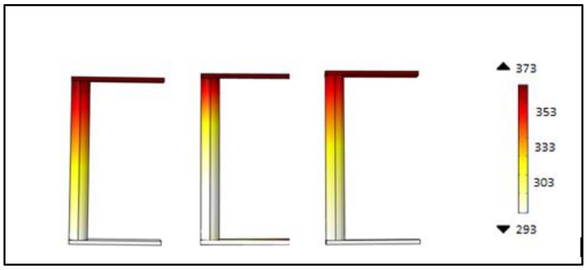
The same process model can be used to obtain the thermal conductivity of the composite. Thus, by varying the CNT filling ratio we can study its effect on conductivity and thermal management.

IV. Simulation and Results

The electrothermal simulation of interconnect with TSVs was carried out using Cu, CNT and Cu-CNT composite. The thermal and electrical analysis are individually discussed below.

A. Thermal Analysis

The temperature of 373 K is applied at the top of interconnect. Its temperature profile obtained is as shown in figure 2. It can be seen that copper does not absorb the heat at a rate as high as CNT. Also when Cu-CNT composite is compared to copper, it shows improvement in the temperature conductivity. Also figure 3 shows the temperature response in case of all the three material. It can be seen that in case of copper, the temperature does not drop suddenly. However, in case of CNT a sudden drop is observed and it is expected to drop below copper with increasing time. This is due to the high thermal conductivity of CNT that results into fast temperature response. It is due to this reason that a



(a) (b) (c)

Figure 2. Temperature profile of interconnect and TSV structure for (a) Copper (b) CNT (c) Cu-CNT composite

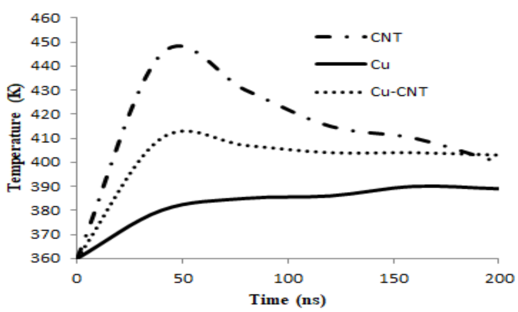
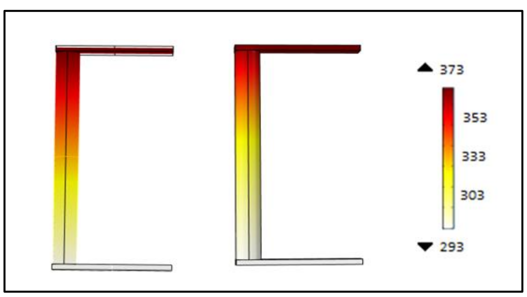


Figure 3. Temperature response for the three different materials when used as TSVs



(a) (b)

Figure 4. Temperature profile for the different proportion of CNT used in the Cu-CNT composite where (a) 0.3 fraction of CNT and (b) 0.7 fraction of CNT in Cu-CNT composite

composite of CNT with Cu is used to enhance the thermal performance of TSVs. Varying the proportion of CNTs will also affect the thermal performance. Figure 4 shows the temperature profile for 0.3 and 0.7 fraction of CNT in the TSV. It can be seen that higher CNT ratio causes greater thermal conductivity. Therefore, it is expected that a densely grown CNT bundle will help to improve the thermal conductivity of TSVs to a higher extent. The interfacial resistance between the TSV and interconnect layers degrade the thermal conductance a bit. However, the effect is less severe in case of CNT-GNR interface than Cu-GNR interface due to the covalent bonds between the CNT-GNR interface help to reduce the thermal resistance.

B. Electrical Analysis

The electrical conductivity of copper is lower than CNT in the nanometer regime. This is because in the nanometer scale copper encounters problems like electromigration and surface roughness scattering. This causes the conductivity of copper to reduce and hence CNTs prove to be useful in low dimension structures, to improve the electrical conductivity.

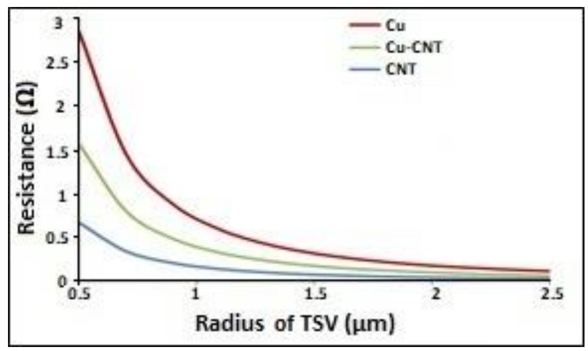


Figure 5. Resistance variation with the radius of TSV for Cu, CNT and Cu-CNT composite

Figure 5 shows how the dimensions of TSVs are related to the resistance offered by the TSVs. A plot of resistance versus the radius of TSV is given. It can be seen that as for lower radius the resistance offered is high for all the three material. Also copper offers the highest resistance and the resistance offered by CNT is the lowest. The composite offers an intermediate resistance of the three materials.

V. Conclusion

In this paper, a electrothermal simulation of interconnect and TSV structure was performed using COMSOL Multiphysics®. Since the metal-GNR contact affects the electrical and thermal resistance of the structure, CNTs were thought of as a replacement to copper as TSV material. However, to improve the reliability and achieve fabricational compatibility, Cu-CNT composite is being proposed. This composite provides advantage over Cu in case of electrical and thermal management, resulting in faster thermal response.

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