Modeling Of 3D Integrated Circuits, Heat Transfer Solutions and Application

Shiyuan Su [1, *], Zhongqi Shi [2], Yile Wang [3]

[1] School of Physical Sciences, Nankai University, Tianjin, 300100, China

[2] Portland Institute, Nanjing University of Posts and Telecommunications, Nanjing, 210000, China

[3] Resources and Materials institute, Northeastern university at Qinhuangdao, qinhuangdao, 066004, China

* Corresponding Author Email: 2011455@mail.nankai.edu.cn

Abstract. As transistor sizes approach the quantum limit, the cost of further shrinking them becomes prohibitively high. To overcome this limitation and surpass Moore's Law, 3D (Integrated Circuits) IC technology has emerged. However, while 3D ICs offer advantages like high integration, they also present challenges related to thermal management. This paper introduces and discusses partial differential equations and modeling methods for heat transfer in 3D ICs. It explores solutions to address thermal conduction problems and analyzes the potential application areas and prospects of 3D ICs. By utilizing different modeling methods, we can optimize the heat transfer problem during the design stage. To enhance the thermal conduction of 3D ICs, this study proposes the use of copper thermal conductive materials, graphene thermal conductive layers, and phase-change material cooling. As technology advances and costs decrease, 3D ICs are expected to find broader applications in high-performance computing, artificial intelligence, the Internet of Things, and other fields. Despite its numerous advantages, 3D integrated circuit technology still faces challenges such as cost, heat, and silicon vias. To address these issues, further technological innovations and updates to Computer Aided Design (CAD) tools are necessary. Overall, this study holds significant social and scientific importance as it promotes the development of 3D IC technology, improves electronic device performance, and advances scientific research.

Keywords: 3D integrated circuits; heat transfer; solution; application.

1. Introduction

Since the introduction of Moore's Law, the development of ICs has closely followed its principles, with the feature size continuously reducing from 90nm to 14nm and even 7nm. However, as transistors approach the quantum limit, the cost of further shrinking them has become prohibitive. To overcome this limitation, 3D integrated circuit technology emerged, offering advantages like low latency, low power consumption, and high integration. However, this advancement also poses challenges, particularly in thermal management. One of the challenges is the rapid increase in leakage current inside the chip, leading to elevated temperatures and localized hotspot areas. Failure to control temperature effectively can ultimately result in chip malfunction [1]. Researchers have attempted to address this thermal management issue by creating physical models to describe the heat conduction in 3D circuits and designing software such as HotSpot [2], 3D-ICE [3], and 3-D-TarGA [4] to aid in thermal reliability analysis during the design stage. However, these modeling approaches simplify the thermal behavior and lack complete accuracy. To enhance cooling in ICs, researchers have proposed highly conductive and reliable thermal interface materials. Yet, their practical implementation faces obstacles such as high cost and complex production processes, hindering widespread adoption of these materials. Despite these challenges, 3D ICs have already found applications in military aviation, medical equipment, and other fields, and they show promise for being extended to everyday electronic devices, including cell phones.

The primary objective of this paper is to explore the analysis and resolution of the thermal conduction problem in 3D ICs. It briefly introduces the heat conduction equations for 3D ICs and discusses methods for thermal modeling analysis. Additionally, it presents commonly used cooling

materials like copper and graphene. Finally, the paper highlights application examples, prospects, and challenges associated with 3D ICs.

2. Modeling and Analysis Methods for Heat Transfer in 3D ICs

This subsection begins by introducing partial differential equations used for analyzing heat transfer problems. It then proceeds to provide a list and comparison of commonly employed modeling and analysis methods.

2.1. Partial Differential Equations

The heat conduction problem in a 2D chip can be formulated in terms of the Fourier heat conduction equation. The equation is shown in equation (1).

$$q=-k_t\nabla T \tag{1}$$

In equation (1), where *q* represents the heat flux, T denotes the temperature, and k_t is the heat transfer coefficient of the material, which is assumed to be isotropic in the general analytical process. Upon reviewing equation (1), it becomes evident that q is directly proportional to the inverse gradient of T, with the thermal conductivity k_t serving as the scaling factor. Equation (2) can be derived from Equation (1).

$$\nabla\cdot q=-k_t\nabla\cdot\nabla T=g(r,t)-\rho c_p\frac{\partial T(r,t)}{\partial t} \tag{2}$$

Where r is the spatial coordinate of a point on the chip; g represents the power consumption density per unit volume; cp is the heat capacity of the material used in the chip; and ρ is the density of the chip material. Equation (2) embodies the fact that the dispersion of heat flux q in a region on the chip is equal to the difference between the power consumption in the region and the rate of change of heat energy in the region over time. Equation (2) can be transformed by a simple transformation to obtain a partial differential equation (PDE) as shown in equation (3). The transient temperature field can be determined by solving equation (3).

$$\rho c_p\frac{\partial T(r,t)}{\partial t}=k_t\nabla^2 T+g(r,t) \tag{3}$$

In real circuits, the time constant of heat transfer is significantly larger, likely on the order of a million seconds [5]. This is far greater than the nanosecond clock period typically seen in VLSI circuits. Consequently, when ICs are operated at constant power consumption for extended periods, the steady-state equations can effectively be used to analyze the heat transfer.

Similarly, during the early stages of chip design, the circuit can also be analyzed using steady-state methods. However, if the circuit undergoes changes in its power consumption pattern at intervals exceeding the thermal conduction time constant, a different approach is needed. In such cases, the circuit must be analyzed using transient methods.

2.2. Modeling Methods for Heat Conduction Problems

When addressing the heat conduction problem, there are primarily two solution methods: analytical solution and numerical solution. While the analytical solution is mathematically feasible and more accurate, obtaining it requires knowing the boundary and initial conditions, which can be challenging to acquire for 3D ICs. In contrast, the numerical solution may not be as precise as the analytical one, but with a well-designed program, it can still provide temperature predictions with a reasonable level of accuracy. As a result, numerical solution methods are commonly employed when analyzing chip heat transfer issues. In this subsection, this paper will focus on listing the different numerical modeling methods currently proposed.

For general heat transfer problems, the finite element method is a widely used modeling approach, known for its high accuracy. Mature Finite Element Method (FEM) modeling software like COMSOL and ANSYS are available for use. However, applying FEM to model 3D ICs necessitates a large

number of meshes, which in turn demands substantial computational resources. To address this challenge, Yudan Pi, Wei Wang, et al. proposed a 3D IC modeling method based on FEM. They achieved this by extracting data and simplifying the geometrical model, allowing them to obtain the system's temperature distribution and heat flux [6].

While the accuracy of modeling using FEM is very high, it requires substantial computational resources. As a result, researchers have explored alternative modeling methods. One such method is the HotSpot modeling proposed by Kevin Skadron et al., which is based on compact thermal models. They demonstrated that the HotSpot model is effective for thermal analysis during the design stage [2]. Although the HotSpot model sacrifices some accuracy compared to the traditional FEM method, it offers significantly higher modeling efficiency.

For simulating 3D ICs with microfluidic cooling, Arvind Sridhar et al. introduced a 3D ICE modeling methodology. They validated this approach using a four-layer 3D integrated circuit model and compared the results to a computational fluid dynamics-based simulation software. The maximum temperature error of the 3D Individual Conditional Expectation (ICE) model was found to be only 3.4%, while achieving a remarkable 975 times speed-up [3].

In this subsection, we introduce several 3D IC modeling methods. It becomes evident that each modeling method has its own set of advantages and disadvantages. There is no universally perfect modeling approach, and choosing the appropriate method depends on the specific requirements in practical applications. It is essential to consider both the thermal and electrical effects on the IC during the modeling process.

3. Solutions to Thermal Issues in 3D ICs

With the emergence of three-dimensional ICs, chip integration has been enhanced, while the size and power consumption have been reduced, among other advantages. However, this development has also brought about thermal effects issues. These thermal effects negatively impact the performance of components and can even lead to component failure. For instance, the rapid increase in leakage current within the chip can cause a further rise in temperature, resulting in localized temperature elevation known as hotspots. Without timely and effective temperature control mechanisms, this can eventually lead to the functional failure of the chip [1]. Traditional experimental methods have become inadequate to cope with the demands of rapid product updates. Therefore, the optimization of heat conduction is primarily focused on the following three aspects.

3.1. Copper Thermal Conductive Material

The selection of thermal conductive materials plays a crucial role in addressing the thermal issues of 3D ICs. Choosing appropriate thermal conductive materials can significantly improve heat dissipation efficiency, thereby reducing chip temperature and enhancing performance and reliability.

For thermal conduction in 3D ICs, copper is one of the more suitable materials. Copper has an extremely high thermal conductivity, it's about 400 W/(m·K) [6], which places it at a higher level among common metals. This means that copper can effectively conduct heat, swiftly transferring heat from the integrated circuit to heat-dissipating components, such as heat sinks or fins. Additionally, copper exhibits good electrical conductivity and mechanical strength. These properties are particularly important in ICs, as copper can simultaneously conduct heat and electricity, ensuring efficient electronic signal transmission and power management while providing sufficient structural support and resistance to external stresses.

3.2. Using Graphene Thermal Layers

Fig. 1 shows a longitudinal cross-sectional schematic of a 3D integrated circuit chip with a two-layer stack, where the black portion represents the graphene thermal layer. The thermal conductivity of graphene is anisotropic [1].

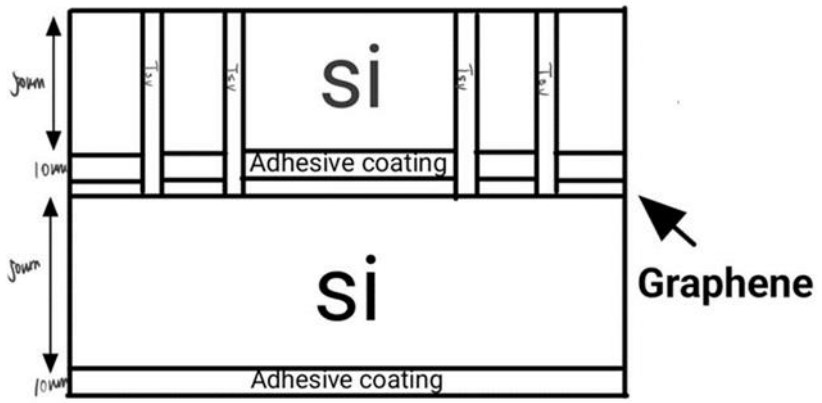


Fig. 1 Longitudinal cross-section of a 3D integrated circuit chip.
https://www.sciencedirect.com/science/article/pii/S1875389212005056

When a heat source is applied to the surface of the first layer chip, the addition of the graphene thermal layer improves the peak temperature significantly as heat flows from top to bottom. This result indicates that the graphene layer provides an effective lateral heat dissipation pathway, enabling rapid dispersion of heat and mitigating the thermal impact of Through-Silicon Vias (TSVs) from the upper layer to the lower layer chip, thereby evening out the temperature on the contact surface.

Similarly, when the heat source is loaded on the upper surface of the second layer chip, where heat flows in both upward and downward directions, the peak temperature at the contact surface is notably reduced. This demonstrates that the graphene layer offers a low thermal resistance lateral pathway, replacing the original high thermal resistance heat channel, resulting in a more uniform temperature distribution on the surface with the heat source loaded.

3.3. Phase Change Material Cooling

Phase Change Material (PCM) is a kind of material that undergo solid-liquid phase transitions at certain temperature ranges under normal pressure. They can be utilized in electronic devices, such as mobile phones and laptops, to absorb heat generated during operation over a specific period. This helps in protecting electronic devices from overheating. Once the PCM absorbs heat, it changes to a liquid state, and when the ambient temperature decreases, it solidifies again through heat dissipation to the surroundings [7].

To enhance the heat dissipation efficiency of heat sinks, phase change materials can be embedded inside them. The working principle of a heat sink filled with PCM is as follows: when the chip temperature rises above the phase change temperature, the PCM starts to absorb heat and undergoes a phase transition. It transfers the heat from the chip to the PCM, storing it in the form of latent heat. Through this process, the heat sink can rapidly absorb and store the heat generated by the chip, preventing the chip from reaching excessively high temperatures.

4. Applications and Prospects of 3D ICs

4.1. Applications of 3D ICs

3D integrated circuit has the characteristics of smaller space, higher performance, more functions and low power consumption. This technology plays an irreplaceable role in various fields of modern science and technology. Table 1 shows the advantages of 3D IC technology in different application fields [8].

The main application areas of 3D ICs are high-end computing, servers and data centers, military and aerospace and medical equipment. It also extends to all kinds of smart devices such as tablets, smartphones and different gaming devices as well as artificial intelligence and machine learning. The

integrated circuit is used to assemble electronic devices, and its assembly density can be increased by dozens to thousands of times compared with the transistor, and the stable working time of the device can also be greatly improved.

Table 1. Advantages of 3D IC technology in different application fields [9].

3D Benefits	Less Power	High Performance	Smaller Size	More Memory	More Bandwidth
Mobile	√	√	√		
High Performance Compute		√		√	√
AR/VR(XR)	√	√	√	√	√
Artificial Intelligence		√		√	
Networking	√	√		√	√
IoT	√		√		

4.2. Commercial Use of 3D ICs

SONY PlayStation Portable (PSP) handheld game console was the earliest known commercial use of a 3D IC chip released in 2004. PSP hardware which consists of eDRAM (embedded DRAM) memory was created by Toshiba in a 3D system-level package chip with two chips piled vertically. Toshiba named it "semi-embedded DRAM" at first, and later called it a piled "chip on a chip" (CoC) solution [10]. Since 2004, chip technology has been constantly updated, and Toshiba, Hynix, Samsung, Micron Technology and other companies continue to use 3D IC for commercial applications.

4.3. Development of 3D ICs

3D integrated circuit technology still faces some challenges. Its manufacturing difficulty is greater than two-dimensional ICs. And it requires a smoother surface layer, more stringent requirements for the interconnection of the circuit, and more stringent temperature and process restrictions for heat treatment.

4.3.1 Cost problem

While cost is an advantage compared to 2D ICs, the issue of cost remains a challenge for commercializing 3D IC in mainstream consumption. Cutting costs requires technological innovation.

4.3.2 Heat problem

The size of the three-dimensional integrated circuit is microscopic, the integration of the chip is greatly improved, and the power consumption is significantly reduced, but the thermal problem is more significant, which may lead to the deterioration of the original performance or even broken. The heat problem is analyzed in the first few parts, and some solutions are provided.

4.3.3 Through Cilicon Via (TSV) problem

3D IC using through-silicon technology have many advantages over traditional single chip, but also face some problems. Compared with two-dimensional ICs, three-dimensional ICs have larger through-silicon vias and need to occupy more space. If the first TSV technology is used, the hole is completed before metallization, and the through hole will occupy the device layer and cause layout obstacles. The application of TSV in 3D IC still needs to continue to improve.

4.3.4 Design complexity

Taking full advantage of 3D IC technology requires sophisticated design techniques and new CAD tools, and current design techniques still need to be updated to meet future 3D IC visions. [11]

4.4. Development Trend of 3D ICs

3D ICs have many advantages over traditional ICs, but they also need to solve the above heat conduction problems and other related problems in future development. With technological innovation, 3D ICs can be more invested in applications to facilitate people's lives.

5. Conclusion

As Moore's Law approaches its limit, 3D ICs have become a way forward beyond traditional 2D ICs, offering numerous advantages. However, thermal management issues have arisen, and new solutions need to be proposed. This paper discusses the development of different integrated circuit modeling approaches, analyzing the advantages and disadvantages of these modeling methods as well as their applicable environments. The advantages of copper, graphene, and phase-change materials as cooling materials are also presented and analyzed, along with the difficulties faced by the large-scale use of these materials, such as high cost and technical complexity. In the future, researchers can optimize heat dissipation at the circuit design stage by selecting or developing appropriate modeling methods and optimizing circuit designs for their needs. More efficient and cheaper cooling materials can also be developed to solve the thermal management problems currently faced by 3D ICs. The research in this thesis is essential for understanding the thermal management problems of 3D ICs and their solutions. The modeling methods and cooling materials presented in this paper help researchers analyze and optimize the thermal conduction problems of 3D circuits. The introduction and outlook on the applications of 3D IC technology can help academia and industry better understand the prospects and challenges of this emerging technology in various fields.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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