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Thermal Management within Three Dimensional Random Access Memory

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Abstract

The thermal energy that computer components such as Random Access Memory (RAM) generate increases with clock speeds. As computer efficiencies continually increase, there is an urgent need for more capable thermal dissipation techniques. This paper explores the usage of diamonds to construct a heat dissipator capable of dissipating the heat released from increasingly faster computer components, specifically, within three dimensional (3D) RAM. RAM within computer chips is an integral part of computer architecture as it allows for extremely fast large scale data access necessary in modern computation. As such, improving RAM density, speed, power consumption, and efficiency would be greatly beneficial for the computing world. Traditionally, RAM has operated on a two dimensional (2D) plane. Modern chips now stack multiple layers of wafers together using Die Stacking technology, with each die stack consisting of hundreds of tiers of transistors, allowing for operation in a third dimension. However, as memory devices have gotten denser with more memory cells per unit volume, the buildup of heat has been a major limitation to further pushing the frontiers of memory clock speeds. This paper introduces an innovative solution using diamonds integrated with transistors to laterally and vertically dissipate excess heat, which can significantly improve the performance of 3D RAM. For simplicity and generality, calculations were run on the Ryzen 5 5600X CPU and found that only 18 μm of diamond thickness are needed to cool the 250 μm chip. This insignificant thickness concludes that this paper's design can be implemented to cool both modern chips and future chips with significantly higher clock speeds.

Keywords: Random access memory, Die stack, Transistor, Diamond heat dissipator, Thermal conductivity, Heat flux

1. Introduction

As computer chips increase in clock frequencies, the heat generated by internal transistors increases drastically. Dissipation of this accumulated heat becomes an increasingly insurmountable industry challenge. Modern computer chips also use a 3D architecture to fit more transistors per unit volume (Lewis and Lee, 2009). These densely packed transistors generate even more heat per unit volume, further increasing their thermal load due to extreme conditions causing on-chip hotspots (Lau and Yue, 2009). If this excess heat is not transferred out of the chip, its performance will significantly decrease and chips will eventually burn out. This necessitates a powerful method for heat dissipation. Modern chips use silicon dioxide as the primary heat dissipator, but with its low thermal conductivity constant of 1.3 W/(mK), a better alternative is a prerequisite for increasing computer chip and transistor speeds. Additionally, modern chips dissipate heat on a whole-chip basis, which means that transistors could heat up neighboring transistors (Mahajan and Chrysler, 2006). Thus, this paper proposes a novel thermal dissipator design for 3D architecture using diamond (thermal conductivity constant of 2200 W/(mK)) to dissipate heat on an individual transistor basis. Leveraging the increased thermal dissipation capacity of diamonds to promptly transport heat out, this paper's design will significantly

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decrease computer chip temperatures so that even more densely packed designs can be constructed with minimal impact on performance.

1.1 Related Works

In the past, the heat generated from 3D die stacked transistors was dissipated through methods such as micro-channel cooling (Venkatadri et al,. 2011) and nanofluids (Wang et al., 2024). The simplified architecture of micro-channel cooling consists of alternating layers of transistors and cooling layers. The cooling layer is a micro-channel of around 20-100 μm thick with a liquid coolant flowing inside it. The heat generated by the transistors flows into the micro-channel and is dissipated laterally out of the chip. However, micro-channel cooling will not be enough to dissipate heat from increasingly faster computer chips. The liquid coolant it usually uses, deionized water, only has a thermal conductivity constant of 0.6 W/(mK), which is orders of magnitude lower than diamond. Additionally, the thickness required by micro-channel cooling is simply too much after considering the total thickness of most computer chips—usually around 250 μm. The use of nanofluids addresses the first limitation, but the thermal dissipation increase is still insufficient to meet the requirements of faster chips. Nanofluids make use of added floating metal or metal oxide particles, such as copper or zinc oxide, to increase the thermal conductivity constant of the liquid to around 0.8 to 1.0 W/(mK).

This paper's proposed method addresses both of the aforementioned limitations. The use of diamond as a heat dissipator increases the thermal conductivity constant from 1.0 W/(mK) to 2200 W/(mK). The diamond layout design also significantly reduces the dissipator thickness required to sufficiently cool modern computer chips. Additionally, micro-channel cooling with nanofluids requires heat to be dissipated laterally, then vertically to a heat sink. This paper's design reduces the distance generated heat needs to travel as it allows heat to travel in all directions at any given time.

1.2 Diamond Innovations

Traditionally, diamond is grown at a temperature of 650-900°C, which is impossible to integrate into device fabrication because of thermal budget constraints. *Development of 300–400 °C grown diamond for semiconductor devices thermal management* by Mohamadali Malakoutian and other researchers addressed this issue (Malakoutian et al., 2023). By introducing oxygen species into diamond growth, they were able to grow diamonds at 300–400 °C while maintaining high sp^3 peaks and minimal sp^2 peaks—similar to traditional diamond growing techniques at 650-900 °C. In chemistry, sp^3 and sp^2 hybridization indicate the number of covalent bonds an atom forms with its neighboring atoms. For carbon in specific, sp^3 hybridization results in carbon forming four single bonds in a tetrahedral shape, while sp^2 hybridization results in one double bond and two single bonds in a trigonal planar arrangement. sp^3 would form diamond, while sp^2 forms graphite, so by maintaining high sp^3 peaks and low sp^2 peaks, Malakoutian and other researchers were able to grow synthetic diamonds at 300–400 °C. This breakthrough has now made diamond computer-chip heat dissipators possible.

2. Proposed Method

Thermal conduction is governed by the Heat Flux Equation (Equation 1), which describes how heat is transferred through media.

$$q_x = -k\frac{dT}{dx} = \frac{k}{L}(T_1 - T_2)$$ Equation 1. Heat Flux Equation

Heat flux (q) is defined to be the amount of heat passing through any given surface. In the context of this paper, the greater the heat flux, the higher the heat dissipation efficiency. Heat flux increases as the thermal conductivity constant (k) increases. Heat flux decreases as distance (x) from the heat source—the transistor—increases. Additionally, the total heat transfer is given by the equation $Q = \int q\, dA$ (simplified to $Q = qA$ for flat-plate constant heat transfer), where A is contact surface area. This means that maximum thermal transfer occurs with a high k value, low x value, and high A value.

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With modern computer chips dissipating heat vertically into a heat sink, lower transistors will heat upper ones. Thus, this paper focuses on both lateral and vertical heat transfer into a material with a high k value—diamond—to facilitate uniform heat dissipation in all directions. Compared to silicon dioxide, the far superior heat transfer efficiency of diamond will significantly reduce heat buildup within the chip and maintain a low internal temperature.

Figure 1 shows a visual representation of one layer of this paper's heat dissipator design. Each individual transistor is encased in synthetic diamond (light blue nodes in Figure 1) to maximize transistor-diamond contact area. Additionally, the circuitry connecting transistors together is also encased in diamond (light green nodes for horizontal connections and dark green nodes for vertical connections) to allow for continuous heat flow and efficient thermal dissipation. This paper's solution also optimizes the x value. Heat is transferred into the heat dissipators immediately after it is produced, meaning that heat flux will be maximized and the heat from one transistor will not heat up other transistors.

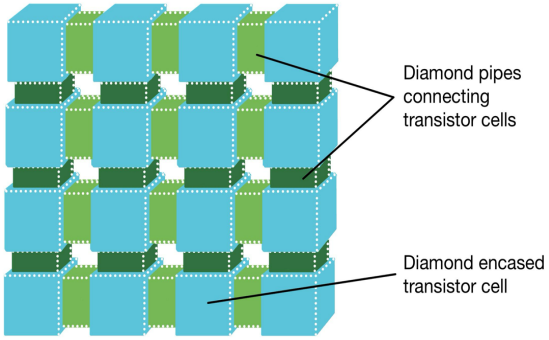

Figure 1. 3D Model of diamond heat dissipator layout for one layer of transistors.

Referencing Figure 2, which depicts a bird's-eye view of this paper's dissipator design, it can be seen that heat can travel in both the x and y directions as diamond (light blue) fully encloses each layer of transistors. With each layer fully encased in diamond vertically stacked together, heat can also travel in the z direction. With heat moving in the x, y, and z directions, this design increases the efficiency of computer chip thermal dissipation significantly as heat will take the shortest path possible to travel to the edge of the chip. Additionally, with heat conducting from transistors to diamond instantly, this design reduces the probability of on-chip hot spot formation, which will ultimately increase the efficiency of modern computer chips.

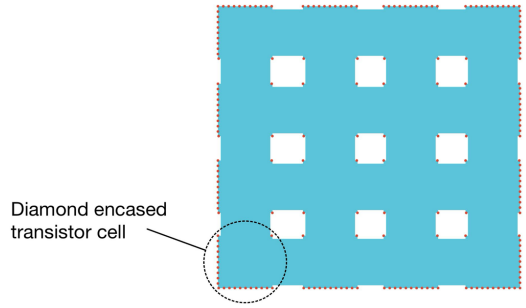

Figure 2. 2D bird's-eye view of diamond heat dissipator layout model.

Modern Graphics Processing Unit (GPU) architecture consists of High Bandwidth Memory (HBM) stacked above the base logic die and interconnected by Through Silicon Via (TSV) to drastically shorten the interconnection distance and reduce latency (Jun et al., 2017). Each HBM stack can be up to 16 die stacks tall, with each die stack consisting of up to 200 tiers of transistors. The tall stack heights mean that lateral heat dissipation is equally as important as vertical dissipation. With this paper's innovative design implemented onto the HBM, the high thermal conductivity of diamond will facilitate efficient heat transfer and reduce heat buildup so the high performance of the GPU chip can be achieved.

3. Results

To validate this paper's proposal, calculations of the required diamond thickness for each layer of transistors were run on a Ryzen 5 5600X CPU—a high performance gaming chip with 6 cores, 12 threads, and boosting up to 4.6 GHz—using the Heat Flux Equation (equation 1). Below are the constant values. L and H are specifications for the Ryzen 5 5600X chip, and k is the thermal conductivity of diamond. For the purposes of this work, a 100K temperature difference between the chip and heat sink is assumed.

$$\Phi_h = \frac{k\Delta T}{L} = \frac{H}{A}$$

$$k = 2200\ \frac{W}{mK}$$

L (distance heat has to travel) = 4.301 mm = 0.004301 m
H (power consumed by CPU) = 65 W
ΔT (temperature difference between chip and heat sink) = 100K

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Upon rewriting the Heat Flux Equation:

$$A = \frac{LH}{k\Delta T} = \frac{(0.004301)(32.5)}{(2200)(100)}\ m^2 \qquad A = 6.354 \times 10^{-7}\ m^2$$

The calculated A value is the total area through which heat must be dissipated to maintain the Ryzen 5 5600X's temperature at 100K above the heat sink temperature. To calculate total diamond layer thickness, A is divided by the total number of sides multiplied by the length of the chip:

$$\text{Total Diamond Thickness} = \frac{A}{(4)(0.008602)} \qquad \text{Total Diamond Thickness} \approx 1.8 \times 10^{-5}\ m$$

This means that to maintain a Ryzen 5 5600X CPU at reasonable working temperatures with the aforementioned assumptions, the required total diamond thickness is only 18 micrometers (μm).

4. Discussion

The Ryzen 5 5600X CPU was chosen to obtain an overhead estimate as CPUs generally consume more power than RAM. For calculation simplicity without underestimating the required total diamond thickness, this paper assumes that half the power the chip draws will be fed to transistors near the center, with the remaining power used for transistors near the edge. L is the distance from the center of the chip to the edge, so L = 0.004301 m and H = $\frac{65}{2}$ W. With these values, the power consumed is halved, but the total distance heat must travel is the maximum value for the chip, resulting in a close approximation for the Ryzen 5 5600X. Additionally, this paper assumes that heat is only dissipated laterally through the sides of the chip. This means that the actual required diamond layer thickness will be lower than what was calculated.

The total diamond thickness was calculated to be 18 μm, and considering the total thickness of the CPU die is approximately 250 μm, the total thickness of diamond heat dissipators will only occupy 7.2% of the total CPU die thickness. This means that this proposed diamond heat dissipator can be integrated within computer chips without significant space penalties. Moreover, this minimal required diamond thickness means additional diamond could be deposited to increase thermal tolerances without the chip incurring any negative ramifications.

Computer chips' heat dissipation will be increasingly bottlenecked by within-chip heat transfer. Modern techniques simply lack the efficiency to deal with this bottleneck due to the low thermal conductivity constant of their used materials. This paper's design introduces a promising pathway to deal with such bottlenecks. The calculated 18 μm thickness would result in performance comparable to modern coolers applied to the Ryzen 5 5600X CPU because of the calculations shown above and the constants used. However, with this design being scalable, as diamond thickness is multiplied by any factor, the thermal performance would also increase by roughly the same factor. Since the required thickness is already miniscule at 18 μm, even a several-fold thickness increase can be easily accommodated by the total chip design. As transistor density within future chips continues to increase, this paper's design will have the capacity to dissipate the drastically increased heat generated by simply increasing diamond thickness.

5. Conclusion

This paper explored a method to increase computer chip thermal dissipator efficiency by proposing a heat dissipator design and assessing its feasibility using the Heat Flux Equation. This paper's design does this by introducing the use of a material—diamond—with significantly higher thermal conductivity than that used in modern dissipators—silicon dioxide. It also facilitates lateral thermal dissipation in addition to vertical dissipation, which reduces cross transistor heating. Completely encasing each transistor in diamond ensures that heat is immediately transferred out of the transistor such that it doesn't negatively affect computer chip performance. From calculations using the Heat Flux Equation on a Ryzen 5 5600X CPU, this design would only require a diamond thickness of 18 μm, which is insignificant compared to the CPU's inherent thickness of 250 μm. Since this paper's calculations only

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assume lateral heat dissipation, the actual required diamond thickness would be much lower than the calculated value, meaning this design is completely feasible to integrate into modern grade computer chips.

A limitation to this work is the added complexity of using internal heat dissipators. Since modern computer chips mostly use external heat dissipation techniques, such as heat sinks, there are few integrated cooling techniques. This paper's design completely goes against this "status quo" as heat is immediately transferred from transistors to internal heat dissipators. These diamond heat dissipators would pose practical fabrication challenges as synthetic diamonds would need to be grown between individual transistors. Although synthetic diamonds can now be grown at 300-400°C, such temperatures would still encroach upon the thermal budget for device fabrication. Additionally, due to the heat dissipator design this paper introduces, the patterning of the diamond layers within the chip still needs to be explored. The etching technologies already exist, but this specific design must be proven on a mass production scale. However, once these challenges are overcome, internal diamond heat dissipators would significantly increase computer chip speeds and efficiency.

A potential direction for future research is the development of designs and methods to optimize heat flow from internal diamond dissipators to an external heat sink. In order to maintain efficient thermal transfer between transistors and diamond, there must be a sufficiently high temperature difference between the two materials. Such a temperature difference can only be achieved if heat is efficiently conducted out of the diamond to be dissipated from the heat sink.

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