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A novel thermal-aware structure of TSV cluster in 3D IC

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ABSTRACT

Although thermal-aware Through Silicon Via (TSV) cluster's behavior has been studied extensively, the structure of TSV cluster, which is also critical for heat dissipation in Three Dimensional Integrated Circuit (3D IC), is ignored. In this paper, a novel structure of TSV cluster is proposed to improve the thermal performance of 3D IC while effectively increasing the area's utilization rate of TSV. Simulation results indicate that the proposed structure benefits both the basic cell and the TSV cluster. Especially, finite element models have been established to study the thermal conduct in the vertical and lateral direction, which shows that the average temperature reduces 0.02% and the peak temperature reduces 0.09% considering the vertical heat dissipation as compared to traditional TSV cluster structure. As for the lateral thermal conduction, the average temperature reduces by 0.005% when the heat source is on the side surface; the peak temperature reduces 0.504% when the heat source is in the middle. Finally, a cluster distribution algorithm is presented to facilitate the implementation of the proposed structure. The results demonstrate that the novel regular triangle structure can effectively alleviate the thermal problem in 3D IC.

1. Introduction

The three-dimensional integrated circuit (3D IC) technology has emerged as a viable solution to overcome the limitations in interconnection and integration complexity as compared to traditional single-layer chip technology. However, there are a number of challenges for 3D IC. With vertical interconnect structure and thinned dies, 3D IC has greater power density. Because of the lower thermal conductivity of the dielectric layers as compared to silicon and metal [1], the heat generated in the device cannot be effectively dissipated, thus, thermal issues are major concerns for 3D IC.

As one of the key technologies for vertical integration, Through Silicon Via (TSV), which is a vertical electrical connection passing completely multiple silicon dies, plays a vital role in 3D IC. Using TSV, 3D IC effectively reduces global interconnect length and makes significant achievements in decreasing delay, reducing power consumption, and minimizing area footprints of chips, as well as increasing integration density. The TSV has relatively high thermal conductivity as compared to the silicon interposer [2], which can effectively alleviate the thermal problem.

In 3D ICs, TSVs are bundled together as a cluster for transferring signal and power, and reducing the temperature between layers [3–5]. Because the dense TSVs have significant impact on the thermal conductivity of the chip, the thermal-aware study of the TSV cluster is a critical part for thermal problem in 3D IC.

Researches on TSV cluster mainly focus on function design, for instance, TSV repair design in [6], cluster error correction in [7], and interconnect design for cluster in [8], but the TSV cluster structure is not discussed in previous work. Some researches concern thermal

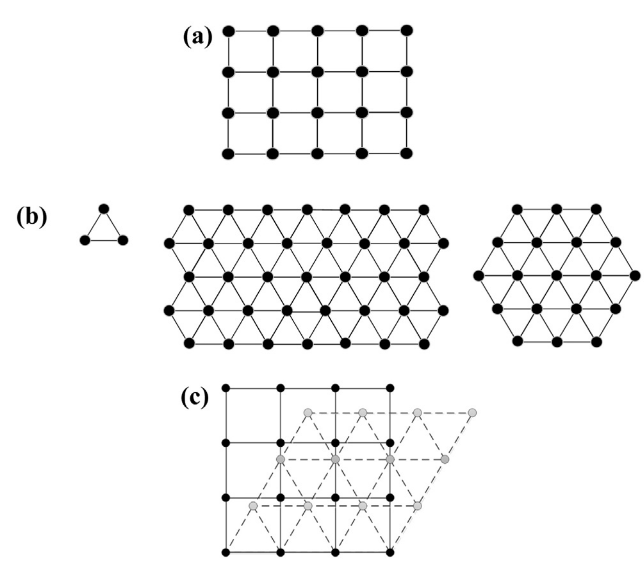

Fig. 1. Structures of TSV cluster. (a) Rectangle grid structure. (b) Regular triangle grid structure. (c) Two types of structures.

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Table 1
Maximum number of TSV in two TSV cluster structures.

Maximum number	Area (μm²)				
	1000	2000	3000	4000	5000
n_{tri}	45	92	138	230	461
n_{rect}	40	80	120	200	400

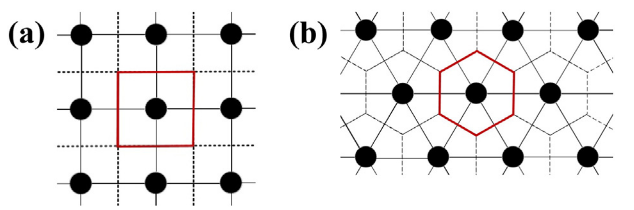

Fig. 2. Basic cells based on one TSV in different TSV clusters. (a) Basic cell of rectangle grid structure. (b) Basic cell of regular triangle grid structure. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

characteristics about TSV cluster. The lateral heat blockage of TSV cluster has been investigated [9]. The technique in [5,9] maximizes the heat flow by removing the via-blockages on the heat dissipation path, but the internal structure of the TSV cluster is not considered. TSVs are constructed to dissipate heat vertically in [10]. However, the influence of TSV cluster structure on the vertical direction of heat transfer is neglected.

In this paper, a novel structure of TSV cluster is proposed to improve the thermal performance of 3D IC both in lateral and vertical heat flow directions. Thermal characteristics of different TSV clusters are also analyzed.

Mathematical methods, such as finite difference (FD) and finite element method (FEM), and tools, such as COMSOL and ANSYS, have been used for performing detailed thermal simulations [11–13]. In this paper, based on software COMSOL, the FEM is used.

The organization of this paper is as follows: In Section 2, with high utilization rate of area, a novel thermal-aware structure of TSV cluster is proposed. In Section 3, to prove that the new structure has better thermal characteristics, thermal-aware simulations on basic cells of different clusters have been conducted. Models have been established to study the characteristics of TSV cluster in two heat flow directions. Section 4 concludes this paper.

2. Methodology

Only equilateral triangle, square and regular hexagonal arrangement can be distributed in close in a plane. Ignoring the equilateral triangular distribution and regular hexagon distribution, the traditional uniform structure of TSV cluster is rectangle grid structure [14–16], which is illustrated in Fig. 1 (a). Adding a TSV in the center of regular hexagonal will become an equilateral triangle distribution. To improve the thermal performance, a novel uniform TSV cluster structure based on the equilateral triangle distribution is proposed, which is illustrated in Fig. 1 (b). The novel structure is called regular triangle grid structure, because the relative position of the adjacent TSVs in the novel structure forms a regular triangle shape. Fig. 1 (b) shows the basic regular triangle and two TSV clusters according to the novel regular triangle grid structure.

The proposed thermal-aware TSV cluster structure can effectively improve the utilization rate of area. The maximum numbers of TSVs across a variety of area are listed in Table 1, with minimum distance among the TSVs is set to 5 μm. It can be observed that in the case of same area, the maximum number of TSV of regular triangle grid structure is 15.25% more than the rectangle grid structure. This is because when the distances between TSVs are the same, the distance of the TSV in the horizontal direction is not changed, but that of the vertical direction is reduced, which can be illustrate in Fig. 1 (c). Thus, the TSV arrangement is more uniform and compact. And the uniformity is the key to better heat transfer. The thermal characteristics of the two structures will be discussed in the next section.

3. Results and discussion

Thermal simulations have been conducted by FEM method widely. To study the thermal performance of TSV cluster, models have been

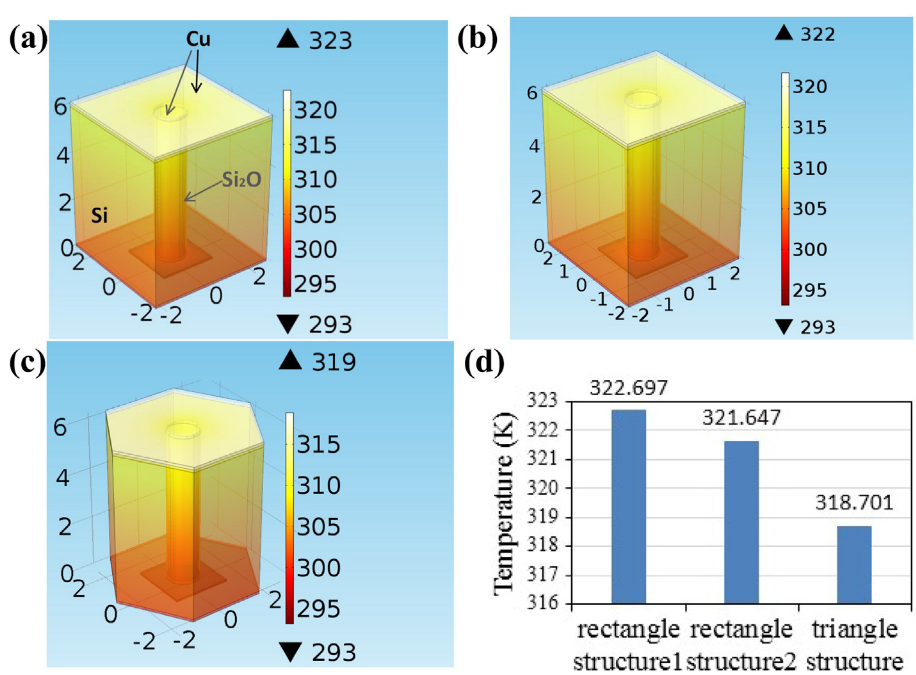

Fig. 3. Basic cells models based on one TSV in different TSV clusters. (a) Basic cell model of rectangle grid structure 1 when the distances between TSVs are equal to (c). (b) Basic cell model of regular rectangle grid structure 2 when the heat source area is equal to (c). (c) Basic cell model of triangle grid structure. (d) Peak temperatures of basic TSV cell models based on one TSV in different structures of TSV clusters.

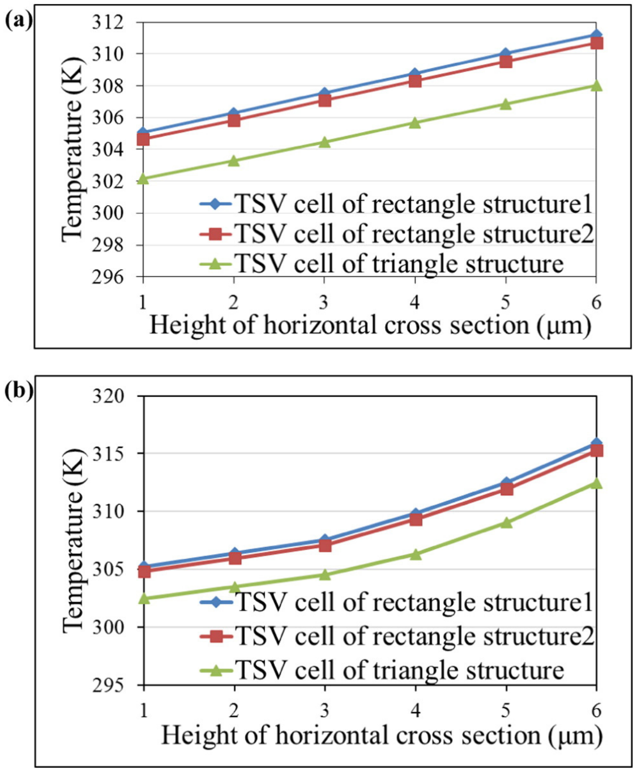

Fig. 4. Temperature in different cross sections. (a) Average temperature of basic TSV cell models based on one TSV. (b) Peak temperature in different cross sections of basic TSV cell models based on one TSV.

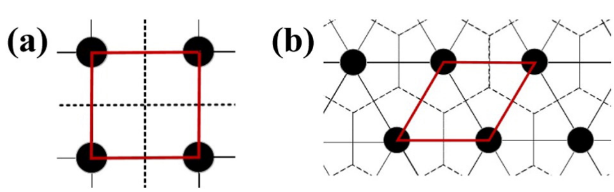

Fig. 5. Basic cell based on four TSVs in different TSV clusters. (a) Basic cell of rectangle grid structure. (b) Basic cell of regular triangle grid structure. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

established by COMSOL software which is based on finite element method. For the models in this section, the parameters of TSVs are the same as the TSV parameters in [17], which is using Tezzaron two-tier 3D stacking technology. According to this, in this paper the diameter of TSV is 1.2 μm, and the height is 6 μm. In these models, silicon, copper, and silicon dioxide are used as the principal material of interposer, TSV and isolation layer respectively, which are shown in Fig. 3 (a). In these models, TSV model is composed of cylindrical copper pillar with a diameter of 5.5 μm and SiO2 insulation layer with thickness of 0.5 μm and wrapped around in copper cylinder.

3.1. Thermal simulations on basic cells of TSV clusters

A TSV cluster of uniform structure can be considered as an array of basic units. In this section, based on the simulations and analysis of the basic units of TSV clusters, the thermal-aware results of TSV clusters with different structures are obtained.

3.1.1. Simulations on single TSV's basic cells

The TSV cluster with uniform structures can be divided into separate TSV's basic cells, shown in Fig. 2. Because these cells are equivalent, they have the same thermal characteristic.

Fig. 3 shows the two thermal simulation models of TSV cell in Fig. 2. In the models, the entire upper surface layer with a thickness of 0.1 μm is set to heat source. The boundary conditions are the same. The bottom surface is set at room temperature and the rest of the surfaces are set to thermal insulation for studying the thermal conductivity in the vertical direction. When the distance between TSVs in Fig. 2 (a) equals to the distance in Fig. 2 (b), the results are shown in Fig. 3 (a) and (c). When the red enclosed area in Fig. 2 (a) equals the red enclosed area in Fig. 2 (b), results are shown in Figs. 3 (b) and (c). The simulation results are shown in Fig. 4.

When the distance between TSVs is constant, the regular triangle structure has higher area utilization. In this case, when a TSV cluster is partitioned evenly, every TSV of traditional structure occupies more area than the novel structure. So, to keep the same power density, the total power of heat sources is set to 5 mW and 4.33 mW in Fig. 3 (a) and (c), respectively. Results show that the average temperature in horizontal cross section of the basic cell model in Fig. 3 (a) is 1.040% larger than that in Fig. 3 (c).

Due to cost and other factors, in various cases the number of TSV is limited. The area utilization of TSV not only affects thermal characteristics of TSV cluster but also the number of TSV. So the further simulation

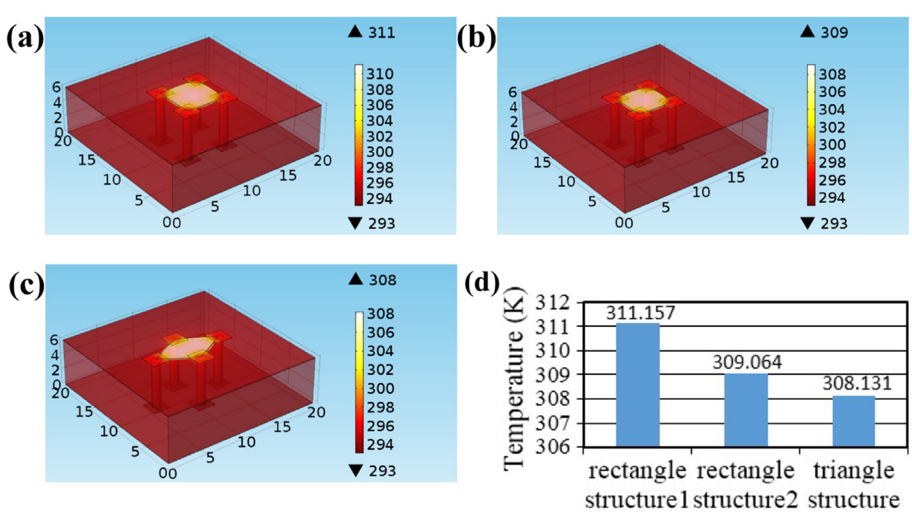

Fig. 6. Basic cell models based on four TSVs in different TSV clusters. (a) Basic cell model of rectangle grid structure 1 when the distances between TSVs are equal to the triangle structure (c). (b) Basic cell model of regular rectangle grid structure 2 when the heat source area is equal to the triangle structure (c). (c) Basic cell model of TSV cluster with triangle grid structure. (d) Peak temperatures of basic TSV cell models based on four TSVs in different structures of TSV clusters.

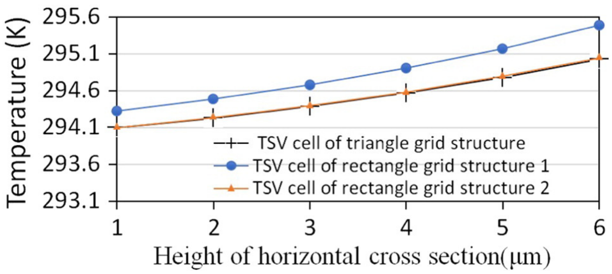

Fig. 7. Average temperatures of basic TSV cell models based on four TSVs in different structures of TSV clusters.

is conducted to study the thermal characteristics of TSV clusters when the area utilization is equal. By adjusting the pitch of TSV, the area of utilization of two cluster structures can be equal, which is shown in Fig. 3 (b) and (c). To keep the same power density, their total power and area of heat sources are equal. The results show that the average temperature in horizontal cross section of the basic cell model in Fig. 3 (b) is 0.880% larger than that in Fig. 3 (c).

These results illustrate that this new structure improves area utilization of TSV and has a better heat transfer even if the area utilization is set to equal that of the conventional pattern. The reason is that the TSV cluster structure has influence on the relative position of the heat source and the TSV, which can affect the heat transfer on chip.

To extend the analysis, the adjacent four TSVs are taken as a basic unit to study the thermal effects between TSVs in different clusters.

3.1.2. Simulations on basic cells with four TSVs of different TSV clusters

The models of basic cells based on four TSVs are established, which is shown in Fig. 6. The heat source is set on the top surface in the light yellow part of the model. Similar to the basic cells based on one TSV. When the distance between TSVs in Fig. 5 (a) is equal to the distance in Fig. 5 (b), results are shown in Fig. 6 (a) and (c). When the red line area in Fig. 5 (a) equals the red line area in Fig. 5 (b), results are shown in Fig. 6 (b) and (c). So, the total powers of heat source are set to 6.18 mW, 5.043 mW, and 5.043 mW, respectively. Simulation results are shown in Fig. 7. When the distance between TSVs is equal, the average temperature of the basic cell model in Fig. 6 (a) is 1.04% higher than that in Fig. 6 (c). When the area utilization of TSV is equal, which is shown in Fig. 6 (b) and (c), the average temperature of the basic cell models is almost equal. Nevertheless, the peak temperatures of the overall models are 311.16 K, 309.06 K, and 308.13 K, respectively, which is shown in Fig. 6 (d). This indicates that the regular triangle TSV cluster structure can affect heat transfer process between the adjacent TSVs. Consequently lower the peak temperature peak temperature i.e. this novel structure does well in reducing the circuit hotspot. Under the same conditions and with four TSVs around the heat sources with equal area, for the structure's reason, the relative position of the heat source and the TSV is various, which leads to the significant difference of the maximum temperature.

By dividing the basic unit of TSV clusters, the heat conduction results of TSV itself and that between four TSVs are obtained. It can be shown that the proposed structure has better uniformity and is able to conduct heat better. It reduces the peak temperature and alleviates the problematic circuit. Next, the overall thermal characteristic analysis of two TSV cluster structures is conducted.

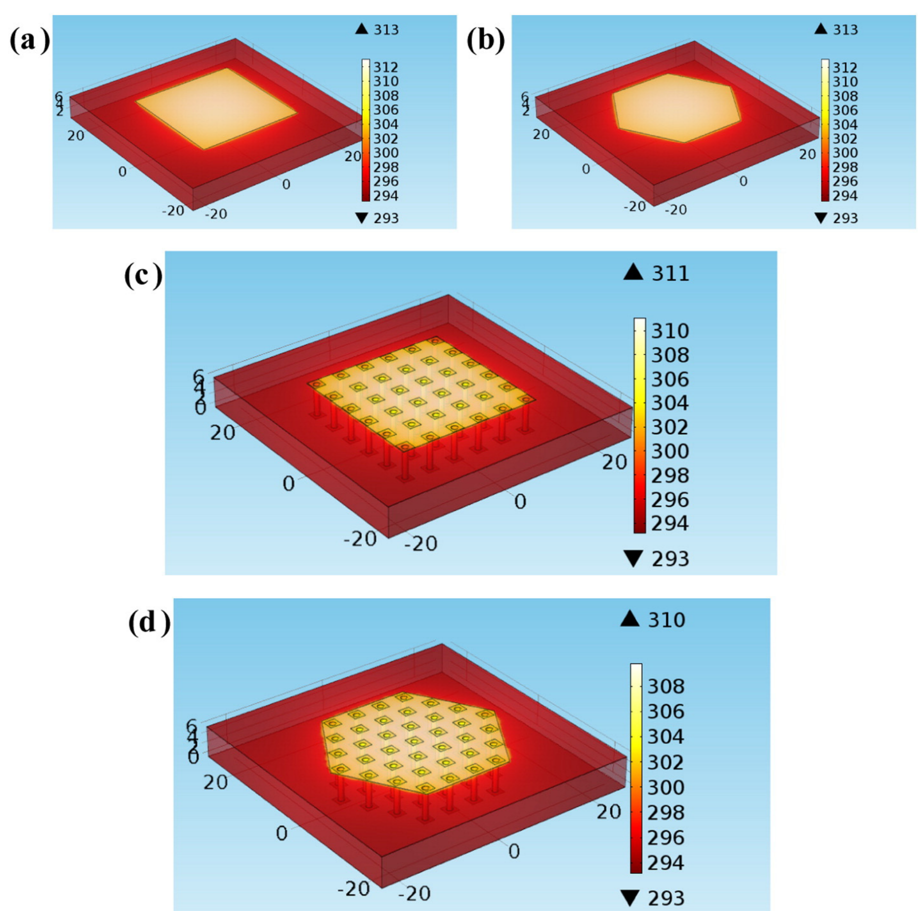

Fig. 8. Models of TSV clusters with heat source on the top. (a) Model with square heat source. (b) Model with hexagonal heat source. (c) Traditional rectangle grid structure of TSV cluster. (d) Novel regular triangle grid structure of TSV cluster.

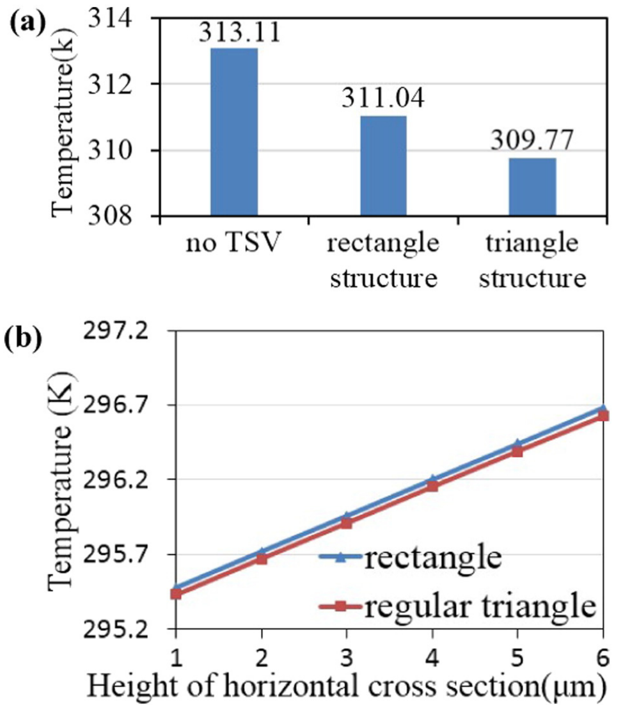

Fig. 9. (a) Peak temperature of models in Figs. (c) and (d). (b) Average temperatures of horizontal cross sections of TSV cluster's models.

3.2. Thermal characteristics of TSV clusters

In 3D IC, the main direction of heat flow is vertical from top to bottom. However, the lateral heat flow also has important influence on the thermal performance. In this section, simulation and analysis on the lateral and vertical heat flow of two TSV clusters are conducted respectively.

3.2.1. Thermal simulation on vertical heat conduction

To study the heat dissipation in vertical, the heat source is set on the top of the Si interposer in the models shown in Fig. 8. Fig. 8 (a) and (b) shows the model without TSV. Fig. 8 (c) shows the TSV cluster's model with rectangle grid structure and the Fig. 8 (d) shows the model with regular triangle grid structure.

For the models in Fig. 8, the heat source area of all models is set to 750.8 μm^2, translating to equivalent power density for all tests. As can be seen, models in Fig. 8 (a) and (b) have the same temperature distribution. Their peak temperature is 313.1 K.

This shows that in the case of the absence of TSV, the simulation results of clusters are the same when they have the same area but different shape of the heat source, which indicates that without TSV the shape of the heat source does no effect on the thermal characteristic. After introducing TSV, the simulation results of models in Fig. 8 (c) and (d) are shown in Fig. 9.

In different heights of horizontal cross sections ranging from 1 μm to 6 μm, the average temperature of the TSV clusters with regular triangle grid structure is reduced by 0.149‰, 0.154‰, 0.161‰, 0.167‰, 0.174‰, and 0.187‰ and the peak temperature is reduced by 0.976‰, 0.998‰, 0.982‰, 0.598‰, 0.763‰, and 1.108‰, as compared to rectangle grid structure. The peak temperatures of the overall models are 311.04 K and 309.77 K. Accordingly, the thermal performance in vertical heat flow of TSV clusters with regular triangle grid structure is better than that with rectangle grid structure.

This is because when the heat source area and the distance between TSVs are unchanged, the novel structure can contain more TSV. The novel structure has contributions in heat conduction.

Table 2
Average temperature of cross sections.

Cross Section in vertical (μm)	Rectangle grid structure	Regular triangle grid structure
−15	299.385	299.367
−5	294.815	294.786
0	294.019	293.994
5	293.607	293.590
15	293.291	293.290

3.2.2. Thermal simulations on heat conduction in lateral

For the models in Fig. 10, the heat source is set on the side surface of the Si interposer to study the heat dissipation in the lateral direction. The simulation results are listed in Table 2.

Table 2 lists that the average temperature of TSV cluster with rectangle grid structure in vertical cross sections is higher than that of the regular triangle grid structure. By reason of the same simulation environment, except for the structure, it can be conclude that these results are caused by the diversity of TSV cluster.

For further study about the heat dissipation in the lateral direction, the heat source is set as a cylinder in the center of the models shown in Fig. 11. For these models, four side surfaces are set at room temperature and the rest of the surfaces are set to thermal insulation. To contrast the thermal conduction capacity, three models are created which are Fig. 11 (a) with one heat source, Fig. 11 (b) with rectangle structure

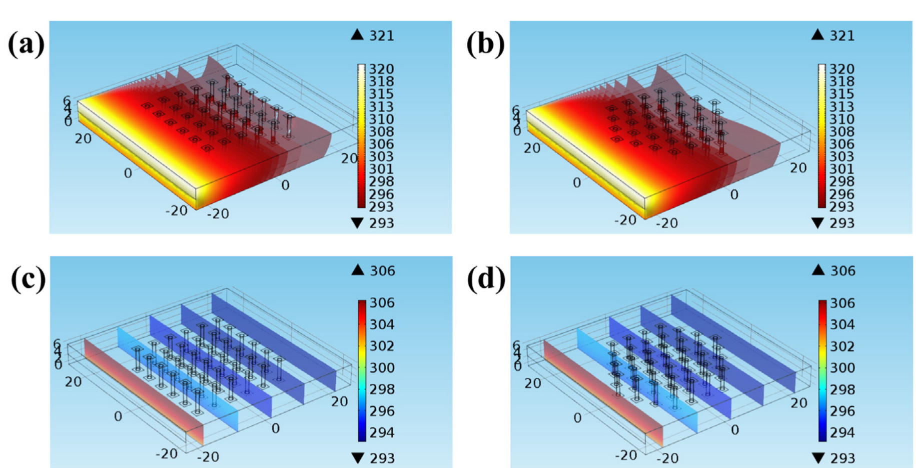

Fig. 10. Models of TSV clusters with heat source on the side. (a) Isothermal surface diagram of rectangle grid structure. (b) Isothermal surface diagram of regular triangle grid structure. (c) Cross sections of rectangle grid structure. (d) Cross sections of triangle grid structure.

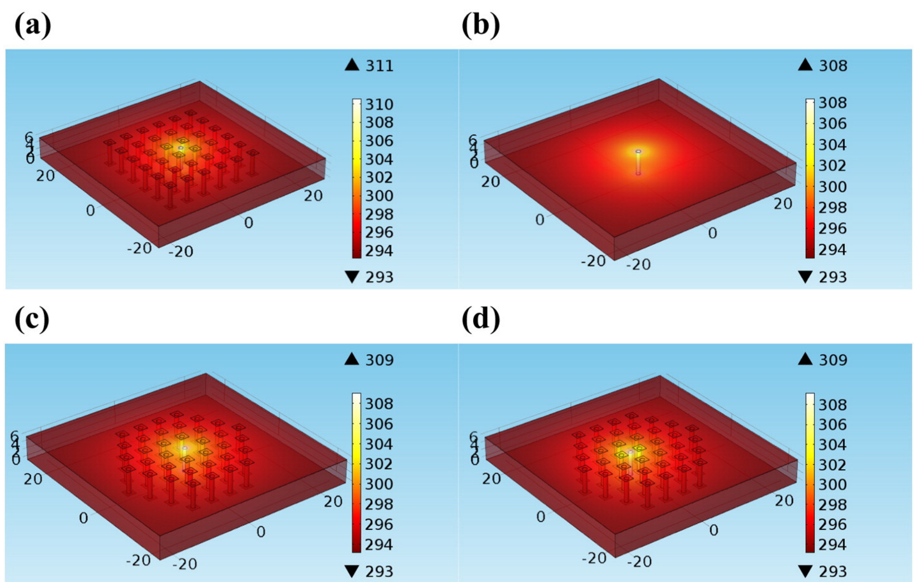

Fig. 11. Models of the TSV cluster with the heat source in the middle cylinder. (a) Model without TSV cluster. (b) Rectangle grid structure. (c) Regular triangle grid structure 1 with heat source in the middle. (d) Regular triangle grid structure 1 with heat source between the middle TSVs.

cluster, and Fig. 11 (c) with triangle structure cluster. Simulation results are shown in Figs. 11 and 12. Obviously, the highest temperature with a rectangle structure TSV cluster is higher than the highest temperature with triangle cluster. For these two models, the variables are not only the structure of the cluster, but also the distance between the heat source and the TSV. Therefore, the triangle structure model in Fig. 11 (d) with the heat source between two adjacent TSVs is established to explore the influence of the distance between heat source and TSV on the lateral heat conduction. In line with the results in Fig. 12, it turns out that it is the structure but not the distance that affects the lateral heat conduction. Whether the heat source is in the middle of the model or between two adjacent TSVs, the peak temperatures of novel structure are lower than that of the traditional one.

The results above indicate the thermal performance in lateral heat flow of TSV clusters with regular triangle grid structure is better than that with rectangle grid structure. This is due to the fact that the lateral heat transfer differs from the vertical one, the heat through the silicon dioxide layer of TSV first, after copper and penetrates out of the silicon dioxide layer, to next TSV until the side surfaces. So the path of heat transfer is mainly determined by the relative position between TSV and TSV. The simulation results show that the triangle structure can transfer heat better than the rectangle structure, but both of them have the function of blocking heat conduction. This is because the silicon dioxide layer has low thermal conductivity so it can hinder lateral heat conduction.

3.3. TSV cluster distribution algorithm

Furthermore, a cluster distribution algorithm has been proposed to facilitate the implementation of the novel cluster structure. The

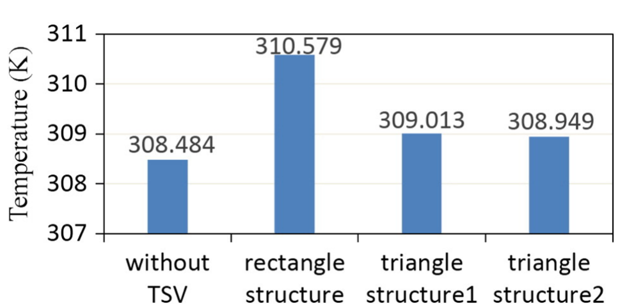

Fig. 12. Peak temperature of the models in Fig. 11.

algorithm adjusts the space between TSVs according to the local power, and then determines the location of each TSV's coordinate, which forms a set of coordinates, {(*x*, *y*)}.

The specific algorithm is shown in Fig. 13, which starts with a judgment with P and P_safe while the area is available (Lines 13, 15, and 19),

```
Algorithm: TSV cluster distribution

1    Input
2      Local power density of the chip    P;
3      Local available area of the TSV cluster    Area;
4      Limit distance range between TSVs R_min<r<R_max;
5      Safety value of the power density    P_safe;
6      Actual distance between the TSVs    r;
7      The TSVs' position    (x, y);
8      The variable    m;
9      The variable    n;
10     The variable    k=1;
11   Output
12     The distribution coordinates set of the TSVs    {(x, y)};

13   While    The area is available
14       Begin
15         If    P> P_safe
16           r= R_min;
17           Make the central of target heat source area as
     coordinate origin;
18           The set of the TSVs' coordinates can be
     presented as following:

19         Else if    P< P_safe;
20           r= R_min*{(P_safe-P)/P_safe+1};
21           Make the central of target heat source area as
     coordinate origin;
22           The set of the TSVs' coordinates can be
     presented as following:

23         Endif
24           k=k+1
25       End
```

Fig. 13. Outline of the novel structure cluster distribution algorithm.

and chooses the coordinate origin (Lines 17 and 21), as well as calculate the set of the TSVs' coordinates (Lines 18 and 22), to obtain the TSV cluster's distribution coordinate set.

4. Conclusion

An innovative structure of TSV cluster and TSV cluster models has been presented in this paper. The proposed thermal-aware TSV cluster structure can effectively improve the thermal performance of 3D IC. Simulation results show that this new structure can improve area utilization of TSV, and has a better heat transfer even if the area utilization is equal. Considering the vertical heat dissipation, the average temperature is reduced by 0.02% and the peak temperature is reduced by 0.09%. As for the lateral thermal conduction, the temperature is reduced by 0.005% on average when the heat source is on the side surface. The peak temperature is reduced by 0.504% when the heat source is in the middle. Furthermore, in lateral direction, the triangle structure can transfer the heat better while the rectangle structure actually blocks the heat conduction. Above all, results indicate that as compared to the traditional structure of TSV cluster, the novel structure can help to ease the thermal problem of the 3D chip.

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