A NOVEL HEAT DISSIPATION STRUCTURE WITH EMBEDDED BOTH THROUGH SILICON VIAS AND MICRO-CHANNELS FOR IMPROVING HEAT TRANSFER PERFORMANCE OF 3-D INTEGRATED CIRCUITS

by

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This paper proposed a new heat dissipation structure with embedded both through silicon vias (TSV) and micro-channels to solve the complex heat problems of 3-D integrated circuits (3-D-IC). The COMSOL simulation model is established to investigate the characteristIC of steady-state response for the defined four cases. The simulation results show that our proposed heat dissipation structure (i.e., Case 4: 3-D-IC with embedded both TSV and micro-channels) can reduce steady-state temperature over 43.546%, 18.440%, and 12.338% in comparison Case 1 (i.e., 3-D-IC without embedded heat dissipation structure), Case 2 (i.e., 3-D-IC with only inserted TSV), and Case 3 (i.e., 3-D-IC with only embedded micro-channels), respectively. Besides, it is demonstrated that CNT as filler material of TSV and CNT nanofluid as coolant of micro-channels (i.e., the proposed Scheme 4) can further reduce steady-state temperature of 3D-IC with embedded our proposed heat dissipation structure. The corresponding results illustrated that the steady-state temperature of Scheme 4 is reduced by 13.767% as compared with Scheme 1 (i.e., the conventional Cu as filler material of TSV and water as coolant of micro-channels). Moreover, it is manifested that the heat transfer performance of 3-D-IC with embedded the proposed heat dissipation structure can be enhanced by the increase of TSV radius and flow rate of coolant of micro-channels. Therefore, our proposed heat dissipation structure has great prospect for enhancing heat transfer performance of 3-D-IC.

Key words*: 3-D-IC, heat dissipation structure, heat transfer performance*

Introduction

The advent of 3-D-IC has given a great impetus to development of semiconductor integrated circuit, which expand the conventional 2-D integrated circuits (2-D-IC) into 3-D space by stacking multiple chips in the vertical direction [1-3]. The 3-D-IC can evidently reduce interconnect length, power consumption and propagation delay as compared with 2-D-IC [4-6]. However, the power density of 3-D-IC will be increased due to the continuously rising of operation frequency and the increasing number of stacked chips in the vertical direction, which

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results in forming the excessive temperature rise of 3-D-IC [7-9]. Hence, it is imperative to improve heat transfer performance for solving the increasingly serious heat problems of 3-D-IC.

To date, the 3-D-IC with inserted TSV in the vertical direction and embedded micro-channels in the silicon substrate are regarded as the two most common solutions for solving the complex heat problems of 3-D-IC. Since the filler material of TSV (usually Cu) possess the high thermal conductivity, thus the heat can be transferred from the multiple stacked dies to TSV in the lateral direction, then can enable it to release from TSV to the external ambient of 3-D-IC by heat sink and package in the vertical direction in time [10-12]. Generally, the micro-channels are embedded in per silicon substrate layer of 3-D-IC, and their interior are filled with the coolant. The flow rate of coolant in micro-channels is depended on pump power and geometric dimensions of micro-channels. The heat is conveyed from the side walls of micro-channel into the coolant, then can be transferred along with the coolant into the outside ambient of 3-D-IC [13-16]

At present, there has been a multitude of researches for using TSV or micro-channels as heat dissipation structures to cope with the extreme heat problems of 3-D-IC. Xiao *et al.* [17] investigated effects of physical parameters of TSV on the heat transfer performance of 3-D-IC, meanwhile the equivalent thermal conductivity of 3-D-IC is obtained by using finite element analysis method. Hou *et al.* [18] proposed a novel structure of TSV cluster and corresponding simulation results indicated that 3-D-IC with inserted novel TSV cluster's structure can clearly enhance heat transfer performance of 3-D-IC. Zajac *et al.* [19] studied the heat transfer performance of 3-D-IC with embedded a single-layer micro-channel under different size of micro-channel by using COMSOL software. The simulation results suggested that increasing the size of the micro-channels and pump power all can improve heat transfer performance of 3-D-IC, meanwhile it is also concluded that excessively increasing the size of micro-channels and pump power can result in diminishing returns of heat transfer performance. Ali *et al.* [20] analyzed heat transfer performance of different shapes of pillar micro-channels (*i.e.*, triangular prism pillar micro-channels, rectangular pillar micro-channels and circular pillar micro-channels), and corresponding experimental results illustrated that the rectangular pillar micro-channels have better heat transfer performance than other pillar micro-channels at over high Reynolds number case. Song *et al.* [21] proposed an numerical model of 3-D-IC with embedded micro-channels, and corresponding results indicated that the 3-D-IC with embedded micro-channels scheme has prominent heat transfer performance. Narayan and Yao [22] the heat transfer performance for different physical parameters of micro-channels is investigated, and corresponding experimental results shown that the volume-average temperature rise decreases as the width of micro-channels increases. Roy *et al.* [23] and Qian *et al.* [24] constructed two different thermal models by using COMSOL software for estimating heat transfer performance of 3-D-IC with inserted TSV case and the 3-D-IC with embedded micro-channels case, respectively, and simulation results suggested that 3-D-IC with embedded TSV or micro-channels all can significantly improve heat transfer performance of 3-D-IC.

Based on the aforementioned discussions, it can be found that most studies with respect to heat dissipation structures of 3-D-IC are focused on the TSV or micro-channels. There is no doubt that TSV or micro-channels all can improve heat transfer performance of 3-D-IC. However, there are still some limitations for them to overcome the continuous increasing temperature rise of 3-D-IC in the practical thermal design. Hence, it is crucial that the chip designer ought to seek new structures with better heat transfer performance to solve these heat problems of 3-D-IC. Based on the available literatures, till date few studies have investigated the heat transfer performance concerning the new structures of 3-D-IC with embedded both TSV and micro-channels. Moreover, it should be noted that the presented results of this paper are not validated with the experimental model. The reason behind this is that the preparation and performance evaluation of 3-D-IC with integrated the proposed heat dissipation structure have strict requirements for the production and testing equipment. Therefore, the COMSOL simulation model regarding our proposed new heat dissipation structures of 3-D-IC with embedded both TSV and micro-channels is established to analyze its heat transfer performance in this paper, which are compared with other heat dissipation structures, including Case 1 (*i.e.*, 3-D-IC without embedded heat dissipation structure), Case 2 (*i.e.*, 3-D-IC with only inserted TSV), and Case 3 (*i.e.*, 3-D-IC with only embedded micro-channels)), respectively. Besides, for ensuring the rationality of simulation model, the effects of temperature on thermophysical properties of TSV filler material and coolant of micro-channels are considered in the proposed simulation model.

In the practical application, the most widely filler material for TSV and the most common coolant for micro-channels are Cu and water, respectively. In order to further improve heat transfer performance of our proposed heat dissipation structure, it is extremely vital to explore new filler material of TSV and new coolant of micro-channels. In recent years, CNT have captured intensive interest from many researchers owing to its excellent electrical and thermal characteristic. The thermal conductivity of CNT can exceed 800 W/mK, while the thermal conductivity for the conventional Cu is only 400 W/mK at room temperature [25]. Hence, the CNT is adopted as a promising candidate for replacing the conventional Cu as filler material of TSV in this work. On the other hand, the thermal conductivity of water is only 0.61 W/mK at room temperature, while the thermal conductivity for CNT nanoparticles as nanofluid can reach to 5.3 W/mK [26]. The nanofluid is the suspension of nanometer-sized materials that is composed of nanoparticles (usually including metals, oxides, or CNT) and base fluid (usually including water or oil) in specific proportions [27, 28]. At present, the nanofluid has become a research hotspot for enhancing heat transfer performance of micro-channels in terms of its excellent thermal properties [29]. Based on the aforementioned discussions, the CNT nanofluid as coolant of micro-channels for improving heat transfer performance of 3-D-IC with integrated our proposed heat dissipation structure is also investigated in this paper due to its high thermal conductivity.

To the best our knowledge, most studies concerning the heat dissipation structures in 3-D-IC are focused on the Case 2 (*i.e.*, 3-D-IC with only inserted TSV) or Case 3 (*i.e.*, 3-D-IC with only embedded micro-channels). Meanwhile, it can be found that the Cu and water are the most widely filler material of TSV and the most common coolant of micro-channels, respectively. Therefore, in order to verify the performance advantage of our proposed heat dissipation structure (*i.e.*, 3-D-IC with embedded both TSV and micro-channels), which are compared with the conventional Case 2 and Case 3 in this paper. Besides, the CNT as filler material of TSV and CNT nanofluid as coolant of micro-channels for further improving heat transfer performance of the proposed heat dissipation structure are also investigated in this work. In addition, the main contributions of this work can be summarized:

- The novel heat dissipation structure is proposed in this work for enhancing heat transfer performance of 3-D-IC.
- The CNT are introduced as filler material of TSV and nanoparticle of nanofluid to further reduce steady-state temperature of 3-D-IC.
- The impacts of the radius of TSV and flow rate of coolant on heat transfer performance of 3-D-IC with integrated our proposed heat dissipation structure are investigated in this work.

Analytical method

The proposed heat dissipation structure regarding the 3-D-IC with embedded both TSV and micro-channels are shown in fig. 1(d). In order to investigate the superiority of heat transfer performance for the proposed heat dissipation structure in 3-D-IC as compared with other conventional heat dissipation structure, the four cases concerning 3-D-IC with embedded different heat dissipation structures are defined as follow, Case 1: 3-D-IC without embedded heat dissipation structure, Case 2: 3-D-IC with only inserted TSV, Case 3: 3-D-IC with only embedded micro-channels, Case 4: 3-D-IC with embedded both TSV and micro-channels, which are exhibited in fig. 1, respectively. Here, the N-layers stacked chip for the defined four cases are bonded in type of face-to-back.

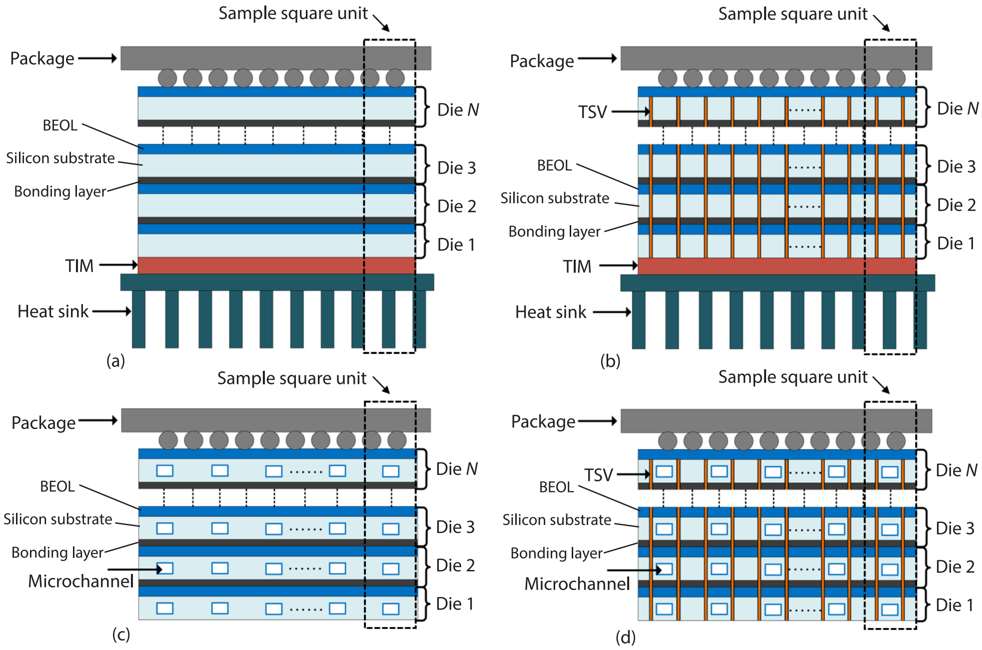

Figure 1. The cross-section diagram of the overall structure for 3-D-IC with embedded different heat dissipation structures; (a) 3D-IC without embedded heat dissipation structure (*i.e.*, Case 1), (b) 3-D-IC with only inserted TSV (*i.e.*, Case 2), (c) 3-D-IC with only embedded micro-channels (*i.e.*, Case 3), and (d) 3-D-IC with embedded both TSV and micro-channels (*i.e.*, Case 4)

As described in figs. 1(a) and 1(b), the structures for Cases 1 and 2 include package, back end of line (BEOL), silicon substrate, bonding layer, thermal interface material (TIM) and heat sink [2]. However, it can be seen from figs. 1(c) and 1(d) that the TIM and heat sink werw not integratet into the defined Cases 3 and 4. These can be explainedthat the bottom surface of the defined Cases 3 and 4 architectures need to provide eletronic and photonic access [30, 31].

As shown in fig. 1(a), the heat generated by BEOL layer is transferred to the external ambient of chip via heat sink and package in the vertical direction for the case of 3-D-IC without embedded heat dissipation structure. The Case 2 as displayed in fig. 1(b), the heat can be transferred by TSV to the heat sink and package in vertical direction. The Case 3 as described in fig. 1(c), the heat can be absorbed by coolant of micro-channels into the external ambient of 3-D-IC. Consequently, for our proposed Case 4, as shown in fig. 1(d), the heat can be conveyed into the external ambient of 3-D-IC by the TSV and micro-channels simultaneously.

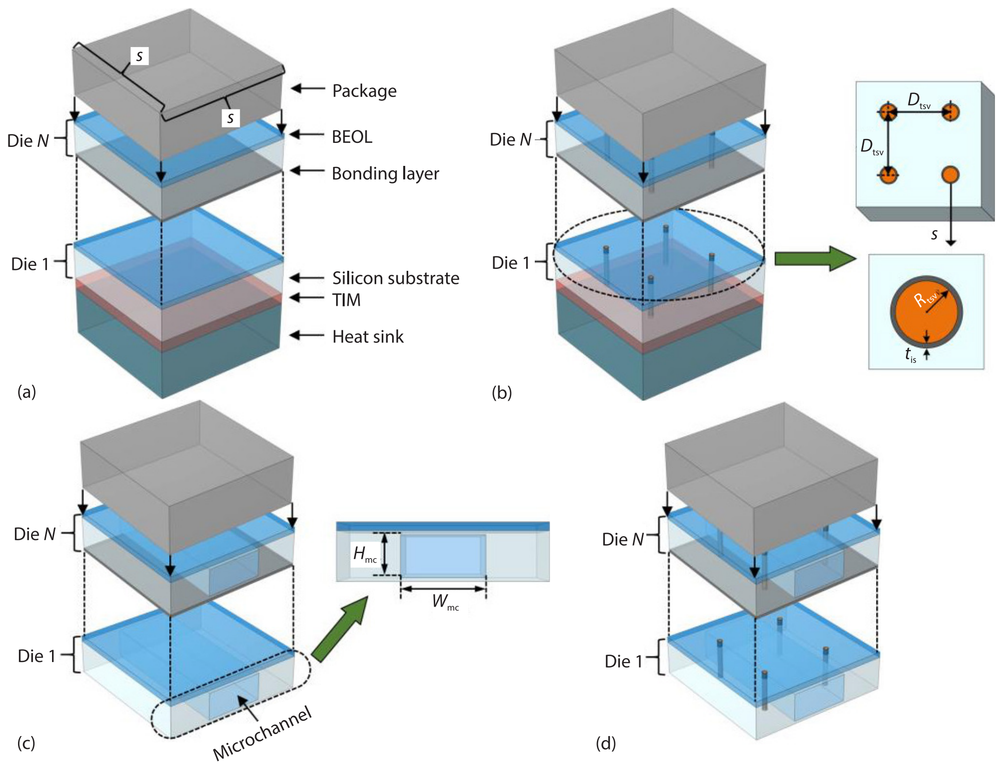

Figure 2. The 3-D view diagrams of sample square unit for 3-D-IC with embedded different heat dissipation structures; (a) 3D-IC without embedded heat dissipation structure (*i.e.*, Case 1), (b) 3-D-IC with only inserted TSV (*i.e.*, Case 2), (c) 3-D-IC with only embedded micro-channels (*i.e.*, Case 3), and (d) 3-D-IC with embedded both TSV and micro-channels (*i.e.*, Case 4)

In order to simplify the analysis, it is assumed for fig. 1 that the micro-channels are uniformly embedded in all silicon layer of 3-D-IC, meanwhile TSV are evenly integrated in 3-D-IC in vertical direction. Since the 3-D-IC can be regarded as a uniform distribution structure with respect to TSV and micro-channels, thus we can utilize the sample square unit to represent the performance of overall 3-D-IC [32]. The 3-D view diagrams of sample square unit regarding the defined four cases are depicted in fig. 2. Especially, it ought to be pointed out for the Case 4 that the micro-channels are evenly distributed in center of silicon substrate of sample square unit, and the columnar TSV cluster are placed in both sides of micro-channels symmetrically. Herein, W_{mc} and H_{mc} are the width and height of micro-channel, respectively. The D_{TSV}, R_{TSV} and t_{is} denote the spacing of center to center of TSV, TSV radius and thickness of insulation medium (usually SiO_2), respectively. The s is the side length of sample square unit of 3-D-IC.

The analytical expression of solid heat transmission can be given [33, 34]:

$$C_v \frac{\mathrm{d}T}{\mathrm{d}t} + \left(-k\nabla^2 T\right) = q_v \tag{1}$$

Similarly, the analytical expression of heat transmission from solid to liquid can be defined [34]:

$$C_v \frac{\mathrm{d}T}{dt} + \nabla\left(-k\nabla T\right) + C_v u_v \nabla T = q_v \tag{2}$$

where k and T represent the thermal conductivity of material and the temperature of material, q_v – the volumetric rate of heat generation of inside the BEOL layer of 3-D-IC, u_v – the velocity of outflow of the fluid at the surface of the control volume, and C_v – the volumetric specific heat capacity of material and its expression can be written [35]:

$$C_v = \rho C_p \tag{3}$$

where ρ and C_p are the density and specific heat capacity of material, respectively.

In order to obtain more accurate calculation results, the effects of temperature on thermophysical properties of both TSV filler material and coolant of micro-channels are considered in this paper. When the Cu is adopted as filler material of TSV, the relationship between temperature and thermophysical properties of Cu can be formulated (0 °C $\ll T \ll$ 100 °C, 0 °C $\ll T_1 <$ 26.85 °C, and 26.85 °C $\ll T_2 \ll$ 100 °C) [36-39]:

$$\begin{aligned} k_{\mathrm{Cu}}(T) &= 762.582657 - 5.70709974(T+273.15) + 0.0364306908(T+273.15)^2 - \\ &-(1.20974465E-4)(T+273.15)^3 + (2.18735712E-7)(T+273.15)^4 - \\ &-(2.04832488E-10)(T+273.15)^5 + (7.77997189E-14)(T+273.15)^6 \end{aligned} \tag{4}$$

$$\rho_{\mathrm{Cu}}(T) = 9062.242 - (3.913962E-1)(T+273.15) - (8.947644E-5)(T+273.15)^2 \tag{5}$$

$$\begin{aligned} C_{p,\mathrm{Cu}}(T_1) &= -215.281402 + 8.23639228(T_1+273.15) - (4.73210818E-2)(T_1+273.15)^2 + \\ &+(1.29111169E-4)(T_1+273.15)^3 - (1.35703145E-7)(T_1+273.15)^4 \end{aligned} \tag{6}$$

$$\begin{aligned} C_{p,\mathrm{Cu}}(T_2) &= 342.764033 + (1.33834821E-1)(T_2+273.15) + \\ &+(5.53525209E-5)(T_2+273.15)^2 - (1.97122089E-7)(T_2+273.15)^3 + \\ &+(1.1407471E-10)(T_2+273.15)^4 \end{aligned} \tag{7}$$

where k_{Cu}, ρ_{Cu} and $C_{p,\mathrm{Cu}}$ are the thermal conductivity, density and specific heat capacity of Cu, respectively.

As the CNT is selected as filler material of TSV, the corresponding relationship between temperature and thermophysical properties can be illustrated as (0 °C $\ll T \ll$ 100 °C) [40]:

$$k_{\mathrm{CNT}}(T) = 637.931556 + 4.1827T - (1.916922E-3)T^2 - (7.022449E-5)T^3 \tag{8}$$

$$C_{p,\mathrm{CNT}}(T) = 815.37142 + 2.0031428T - (1.2857E-3)T^2 \tag{9}$$

$$\alpha_{\mathrm{CNT}}(T) = 4.4623074E-4 + (7.85775E-8)T + (2.0125771E-8)T^2 - (1.92435E-10)T^3 \tag{10}$$

where k_{CNT}, $C_{p,\mathrm{CNT}}$, and α_{CNT} represent the thermal conductivity, specific heat capacity and thermal diffusivity of CNT, respectively. The function relationship between the density of CNT, ρ_{CNT}, and temperature can be calculated [41]:

$$\rho_{\mathrm{CNT}}(T) = \frac{k_{\mathrm{CNT}}(T)}{\alpha_{\mathrm{CNT}}(T) C_{p,\mathrm{CNT}}(T)} \tag{11}$$

When the water is chosen as coolant of micro-channels, the analytical expressions concerning temperature and thermophysical properties of water can be defined (0 °C $\ll T \ll$ 100 °C) [42]:

$$k_{\mathrm{wt}}(T) = 0.56112 + (1.93E-3)T - (2.60152749E-6)T^2 - (6.08803E-8)T^3 \tag{12}$$

$$\rho_{\mathrm{wt}}(T)=1000\left[1-\frac{(T-4)^2}{119000+1365T-4T^2}\right] \tag{13}$$

$$C_{p,\mathrm{wt}}(T)=4217.629-3.20888T+(9.503E-2)T^2-(1.32E-3)T^3+ \\ +(9.415E-6)T^4-(2.5479E-8)T^5 \tag{14}$$

where k_{wt}, ρ_{wt}, and $C_{p,\mathrm{wt}}$ are the thermal conductivity, density and specific heat capacity of pure water, respectively.

For the CNT nanofluid as coolant of micro-channels, the relationship between temperature and thermophysical properties of CNT nanofluid can be defined [43-45]:

$$k_{\text{wt-CNT}}(T)=\frac{1-\phi+\left(\frac{4\phi}{\pi}\right)\sqrt{\frac{k_{\mathrm{CNT}}(T)}{k_{\mathrm{wt}}(T)}}\operatorname{arctg}\left(\frac{\pi}{4}\sqrt{\frac{k_{\mathrm{CNT}}(T)}{k_{\mathrm{wt}}(T)}}\right)}{1-\phi+\left(\frac{4\phi}{\pi}\right)\sqrt{\frac{k_{\mathrm{wt}}(T)}{k_{\mathrm{CNT}}(T)}}\operatorname{arctg}\left(\frac{\pi}{4}\sqrt{\frac{k_{\mathrm{CNT}}(T)}{k_{\mathrm{wt}}(T)}}\right)}k_{\mathrm{wt}}(T) \tag{15}$$

$$\rho_{\text{wt-CNT}}(T)=\phi\rho_{\mathrm{CNT}}(T)+(1-\phi)\rho_{\mathrm{wt}}(T) \tag{16}$$

$$C_{p,\text{wt-CNT}}(T)=\phi C_{p,\mathrm{CNT}}(T)+(1-\phi)C_{p,\mathrm{wt}}(T) \tag{17}$$

where ϕ is the volume fraction of CNT, $k_{\text{wt-CNT}}$, $\rho_{\text{wt-CNT}}$, and $C_{p,\text{wt-CNT}}$ are the thermal conductivity, density and specific heat capacity of CNT nanofluid, respectively.

Results and discussions

This section will investigate the heat transfer performance of our proposed heat dissipation structure of 3-D-IC (*i.e.*, 3-D-IC with embedded both TSV and micro-channels), where a five-layers stacked chip is investigated. In order to prove the performance advantage of our proposed heat dissipation structure, we defined the four cases as below, Case 1: the 3-D-IC without embedded heat dissipation structure. Case 2: the 3-D-IC with only inserted TSV, Case 3: the 3-D-IC with only embedded micro-channels, and Case 4: the 3-D-IC with embedded both TSV and micro-channels (*i.e.*, our proposed heat dissipation structure of 3-D-IC). In this work, the inlet temperature of coolant and ambient temperature are set as 20 °C and 26 °C, respectively [46]. Additionally, it is defined that all die layers are configured the same physical geometry structure. The amount of heat generation of per BEOL layer is set as $2E10$ W/m^3, and other physical parameters of 3-D-IC are shown in tab. 1 [47-53]. All the calculation results presented in the following section are executed by using the COMSOL 6.0 software. The details of modelling approach for COMSOL simulation are listed as follows [54]:

– The heat transfer in solid module is applied in Cases 1 and 2 for COMSOL simulation. While the heat transfer in solid and fluid heat transfer module are coupled by using the non-isothermal flow feature in COMSOL simulation for Cases 3 and 4.
– The total amount of heat generated by heat source is fixed, which is uniformly distributed on each BEOL.
– The coolant flow is assumed to be steady, laminar and fully developed in each micro-channel.
– The pressure outlet boundary condition of micro-channel is adopted as zero gradients.
– The surfaces of micro-channel walls are not affected by slip conditions.

Table 1. The physical and geometric parameters of 3-D-IC

Parameters	Values
Chip size and square analysis unit size	2000 μm × 2000 μm, 250 μm × 250 μm
Thickness of insulating layer and distance of center to center of TSV	0.5 μm, 125 μm
Width and height of micro-channels	100 μm, 50 μm
Thickness of package, BEOL, silicon substrate, bonding layer, TIM and heat sink	150 μm, 10 μm, 60 μm, 5 μm, 20 μm, 200 μm,
Density, specific heat capacity and thermal conductivity of package	6240 kg/m^3, 421 J/kgK, 226 W/mK
Density, specific heat capacity and thermal conductivity of BEOL	2200 kg/m^3, 517 J/kgK, 2.25 W/mK
Density, specific heat capacity and thermal conductivity of silicon substrate	2328.3 kg/m^3, 700 J/kgK, 150 W/mK
Density, specific heat capacity and thermal conductivity of bonding layer	1400 kg/m^3, 1100 J/kgK, 0.3 W/mK
Density, specific heat capacity and thermal conductivity of TIM	2077 kg/m^3, 870 J/kgK, 14.416 W/mK
Density, specific heat capacity and thermal conductivity of heat sink	2688.9 kg/m^3, 902 J/kgK, 237 W/mK
Density, specific heat capacity and thermal conductivity of insulating layer	2200 kg/m^3, 765 J/kgK, 1.4 W/mK

Heat transfer performance of 3-D-IC with embedded novel heat dissipation structure

In order to validate the performance superiority of our proposed heat dissipation structure of 3-D-IC, the temperature results of steady-state and transient responses under the defined four cases are investigated, respectively. The transient temperature results for the defined four cases are exhibited in fig. 3. Here, the TSV radius and the flow rate of coolant are set as 4 μm and 4 mL per minute, respectively.

As shown in fig. 3, it is obviously that the swing of temperature fluctuation for the Case 1 is larger than all other cases. The reason for this phenomenon is that the heat generation in per BEOL layer cannot be timely transferred to the external environment of 3-D-IC for the Case 1. In addition, the characteristic of steady-state response of the defined four cases are investigated, the corresponding steady-state temperature results of all die stacked layer are listed in tab. 2.

As displayed in tab. 2, it is implied that our proposed heat dissipation structure (*i.e.*, Case 4) can remarkably reduce the steady-state temperature of all stacked layer in comparison Cases 1-3. Taking the $i = 5$ die layer as an example, the steady-state temperature for Case 4 is reduced over 43.546%, 18.440%, and 12.338%, respectively, as compared with Cases 1-3. Therefore, our proposed heat dissipation structure with embedded both TSV and micro-channels can effectively improve heat transfer performance of 3-D-IC.

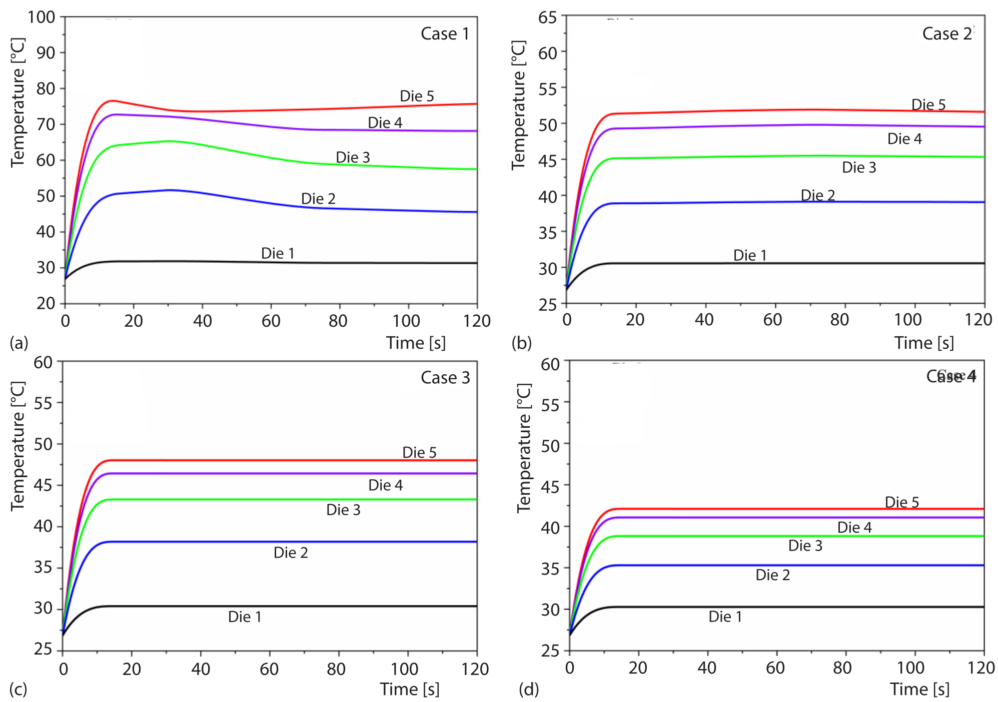

Figure 3. The transient temperature results of per die layer; (a) 3-D-IC without embedded heat dissipation structure case (*i.e.*, Case 1), (b) the 3-D-IC with only inserted TSV case (*i.e.*, Case 2), (c) 3-D-IC with only embedded micro-channels case (*i.e.*, Case 3), and (d) the 3-D-IC with embedded both TSV and micro-channels case (*i.e.*, case 4)

Table 2. The steady-state temperature of all die layer for the defined four cases

Method	TSV radius	Flow rate of coolant	Steady-state temperature of ith die layer [°C]				
			i = 1	*i* = 2	*i* = 3	*i* = 4	*i* = 5
Case 1	–	–	31.590	48.788	61.685	70.279	74.570
Case 2	4 μm	–	30.560	39.005	45.317	49.531	51.616
Case 3	–	4 mL per minute	30.409	38.192	43.292	46.438	48.023
Case 4	4 μm	4 mL per minute	30.277	35.298	38.820	41.056	42.098

Application of CNT in enhancing heat transfer performance of 3-D-IC

The CNT as the filler material of TSV and nanoparticles of nanofluid of micro-channels are investigated in this section, respectively, which are adopted as the solutions for enhancing heat transfer performance of 3-D-IC. In addition, the effects of TSV radius and flow rate of coolant on the steady-state temperature results of all die layer of 3-D-IC are also analyzed, respectively.

The heat transfer performance of 3-D-IC concerning CNT for substituting the conventional Cu as filler material of TSV

The CNT as a promising candidate for replacing the traditional Cu as filler material of TSV are studied to improve heat transfer performance of 3-D-IC in this work. Here, only the defined Case 4 for utilizing CNT and Cu as filler material of TSV are investigated, the corresponding steady-state results are shown in fig. 4.

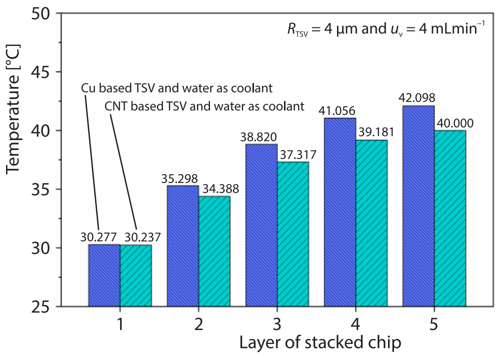

Figure 4. The steady-state temperature results of all die layer under the defined Case 4 for using the Cu and CNT as filler materials of TSV

As exhibited in fig. 4, it can be observed that the steady-state temperature for CNT based TSV case is lower than Cu based TSV case. Giving the i = 4 die layer as an instance, the temperature for CNT based TSV case is reduced over 4.567% than the conventional Cu based TSV case. In addition, the effects of TSV radius on temperature of all die layer are studied, and the corresponding results are illustrated in tab. 3.

As described in tab. 3, it is indicated that increasing the TSV radius can effectively reduce steady-state temperature of all die layer. For instance, when the TSV radius R_{TSV} increases from 2-6 μm, the percentage reduction of steady-state temperature is 15.035% at the i = 4 die layer. Therefore, increasing the TSV radius is an effective way to reduce the temperature of 3-D-IC. Moreover, it should be pointed out that the increase of TSV radius will reduce the lay-out space of transistor devices and interconnect wires in 3-D-IC.

Table 3. The steady-state temperature of all die layer for CNT based TSV with different TSV radius

Method	TSV radius	Flow rate of coolant	Steady-state temperature of ith die layer [°C]				
			i = 1	i = 2	i = 3	i = 4	i = 5
CNT based TSV and water as coolant	2 μm	4 mL per minute	30.310	36.408	40.549	43.160	44.411
	3 μm	4 mL per minute	30.265	35.322	38.819	41.051	42.008
	4 μm	4 mL per minute	30.237	34.388	37.317	39.181	40.000
	5 μm	4 mL per minute	30.192	33.696	36.178	37.794	38.405
	6 μm	4 mL per minute	30.150	33.152	35.279	36.671	37.155

The heat transfer performance of 3-D-IC concerning CNT nanofluid for substituting the conventional water as coolant of micro-channels

In this section, the CNT nanofluid for replacing the conventional water as the coolant of micro-channels for promoting heat transfer performance of 3-D-IC is discussed. Herein, only the defined Case 4 for water and CNT nanofluid as coolants are investigated, respectively, and corresponding steady-state temperature results are shown in fig. 5. In addition, the filler material of TSV is adopted as Cu for the defined Case 4, meanwhile the volume fraction of CNT nanoparticles of nanofluid is configured as 0.1.

As depicted in fig. 5, it can be seen that the CNT nanofluid as coolant case has lower steady-state temperature than the conventional water as coolant scheme. Using the $i = 3$ die layer as an example, the temperature of water as coolant scheme is larger than 1.105 times than CNT nanofluid as coolant case. The reason behind this is that CNT nanofluid has a lesser thermal conductivity as compared with water.

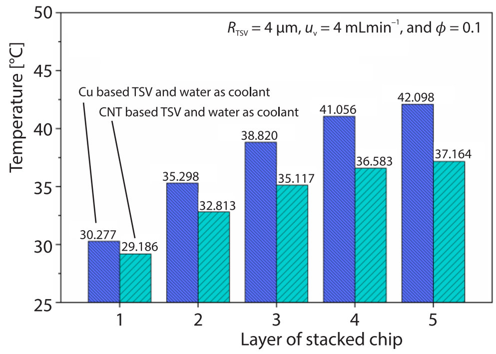

Figure 5. The steady-state temperature results of all die layer for the defined Case 4 under the water and CNT nanofluid as the coolants of micro-channels

Additionally, the impacts of coolant flow rate of micro-channels on steady-state temperature of all die layer are shown in tab. 4, where the coolant of micro-channels is selected as CNT nanofluid. Table 4 indicates that increasing the flow rate of coolant can significantly reduce the steady-state temperature of all die layer of 3-D-IC. For instance, the steady-state temperature can be reduced over 15.945% when the flow rate of coolant u_v increases from 2 mL per minute to 6 mL per minute at the $i = 3$ die layer. Therefore, increasing the flow rate of coolant can evidently enhance heat transfer performance of 3-D-IC. In addition, it ought to be stated that the increase in flow rate of coolant is due to the increase of pump power.

Table 4. The steady-state temperature of all die layer for CNT nanofluid as coolant with different flow rate of coolant

Method	TSV radius	Flow rate of coolant	Steady-state temperature of ith die layer [°C]				
			$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
Cu based TSV and CNT nanofluid as coolant	4 μm	2 mL per minute	29.977	35.412	39.129	41.540	42.548
	4 μm	3 mL per minute	29.520	33.901	36.787	38.638	39.389
	4 μm	4 mL per minute	29.186	32.813	35.117	36.583	37.164
	4 μm	5 mL per minute	28.927	31.988	33.865	35.052	35.513
	4 μm	6 mL per minute	28.720	31.337	32.890	33.868	34.244

The heat transfer performance of 3-D-IC with embedded both CNT as filler material of TSV and CNT nanofluid as coolant of micro-channels

On the basis of the aforementioned discussions, the heat transfer performance of 3-D-IC with embedded both CNT as filler material of TSV and CNT nanofluid as coolant of micro-channels are investigated in this section. The corresponding steady-state temperature results for the defined Case 4 are depicted in fig. 6. Here, in order to analyze conveniently, we defined the four schemes as follows, Scheme 1: the filler material of TSV is adopted as the conventional Cu, and the coolant of micro-channels is configured as the conventional water. Scheme 2: the filler material of TSV is adopted as the CNT, and the coolant of micro-channels is also configured as the conventional water. Scheme 3: the filler material of TSV is also adopted as the conventional Cu, and the coolant of micro-channels is configured as the CNT nanofluid. Scheme 4: the filler material of TSV is adopted as the CNT, and the coolant of micro-channels is configured as the CNT nanofluid.

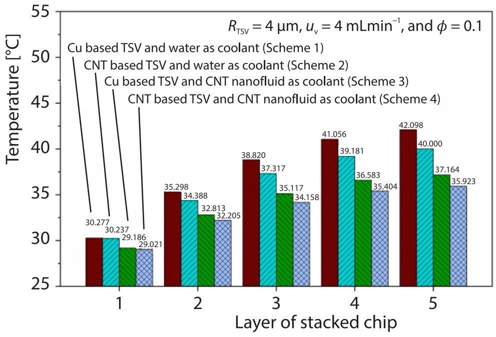

Figure 6. The steady-state temperature results of all die layer for the defined Case 4 under the defined four schemes

Figure 6 shows that the proposed Scheme 4 has lower steady-state temperature than all other schemes (*i.e.*, Schemes 1-3). As an instance, for the i = 4 die layer, the steady-state temperature of Scheme 4 is reduced by 13.767%, 10.895%, and 4.567% in comparison Schemes 1-3, respectively. Consequently, the proposed Scheme 4 (*i.e.*, 3-D-IC with embedded both CNT as filler material of TSV and CNT nanofluid as coolant of micro-channels) can be regarded as a prospective approach for enhancing heat transfer performance of 3-D-IC.

Besides, the influences of TSV radius and flow rate of coolant on the steady-state temperature of 3-D-IC are studied. And the corresponding steady-state temperature results with different TSV radius and flow rate of coolant are listed in tab. 5. Here, only the proposed Scheme 4 is investigated.

As illustrated in tab. 5, it is suggested that increasing both TSV radius and flow rate of coolant can further enhance heat transfer performance of 3-D-IC. Taking the i = 3 die layer as an example, the steady-state temperature for R_{TSV} = 2 μm and u_v =2 mL per minute case is 1.271 times larger than R_{TSV} = 6 μm and u_v =6 mL per minute case. Therefore, increasing the TSV radius and flow rate of coolant of micro-channels can greatly improve heat transfer performance of 3-D-IC.

Table 5. The steady-state temperature results of all die layer for different TSV radius and flow rate of coolant

Method	TSV radius	Flow rate of coolant	Steady-state temperature of ith die layer [°C]				
			i = 1	i = 2	i = 3	i = 4	i = 5
Scheme 4	2 μm	2 mL per minute	30.076	36.161	40.293	42.899	44.130
	3 μm	3 mL per minute	29.484	33.695	36.442	38.173	38.897
	4 μm	4 mL per minute	29.021	32.205	34.158	35.404	35.923
	5 μm	5 mL per minute	28.793	31.247	32.702	33.638	33.965
	6 μm	6 mL per minute	28.625	30.576	31.696	32.426	32.649

Conclusions

A new heat dissipation structure concerning 3D-IC with embedded both TSV and micro-channels (*i.e.*, the proposed Case 4) is proposed to enhance heat transfer performance of 3-D-IC in this paper. The COMSOL simulation model for the defined four cases is established to analyze heat transfer performance of steady-state and transient responses, respectively, which take the effects of temperature on filler material of TSV and coolant of micro-channels into consideration in this work. The main findings of this work are as follows.

- Our proposed heat dissipation structure (*i.e.*, the proposed Case 4) can remarkably enhance heat transfer performance of 3-D-IC. The steady-state temperature for Case 4 is reduced over 43.546%, 18.440%, and 12.338%, respectively, as compared with the defined Cases 1-3.

- The proposed Scheme 4 can be regarded as a prospective approach for improving heat transfer performance of 3-D-IC. For the proposed Case 4, the steady-state temperature of Scheme 4 can be reduced by 13.767%, 10.895%, and 4.567% as compared with the defined Scheme 1-3, respectively.
- The heat transfer performance of 3-D-IC with integrated the proposed heat dissipation structure can be further improved by the increase of TSV radius and flow rate of coolant of micro-channels.

Based on the presented results in this paper, our proposed new heat dissipation structure would be beneficial in enhancing heat transfer performance to solve the complex heat problems of 3-D-IC. However, it must be emphasized that the preparation of 3-D-IC with integrated the proposed heat dissipation structure requires the sophisticated equipment, meanwhile have also the high requirement in the complex fabrication procedures. Therefore, the fabrication of 3-D-IC with integrated the proposed heat dissipation structure might be the biggest challenge in the practical application.

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