

INTEGRATED MICROCHANNEL COOLING IN A THREE DIMENSIONAL INTEGRATED CIRCUIT A Thermal Management

by

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Microchannel cooling is a promising technology for solving the three-dimensional integrated circuit thermal problems. However, the relationship between the microchannel cooling parameters and thermal behavior of the three dimensional integrated circuit is complex and difficult to understand. In this paper, we perform a detailed evaluation of the influence of the microchannel structure and the parameters of the cooling liquid on steady-state temperature profiles. The results presented in this paper are expected to aid in the development of thermal design guidelines for three dimensional integrated circuit with microchannel cooling.

Key words: *thermal, three-dimensional integrated circuit, microchannel*

Introduction

Three-dimensional integrated circuit (3D-IC) technology, emerging as a powerful tool for satisfying the challenging integrated circuit packaging requirements, has received considerable attention in the semiconductor community [1-3]. By expanding the design space into the third dimension, 3D-IC offer several advantages over the traditional microelectronic designs, including reduced average wire length, wire delay, power consumption and footprint, etc. [4, 5]. Although the electrical benefits are proved to have great improvements in stacked integrated circuit (IC) packages, as the package density increases, the heat quantity in each unit volume becomes higher, which will greatly increase the working temperature of the device. The problems of heat dissipation are more serious and catching lots of attentions than those in the traditional single IC package. Hence, thermal management for 3D-IC is becoming a major concern [6-8].

In recent years, the microchannel cooling technology is a promising technology for solving the thermal problems of the 3D-IC [9,10]. However, the microchannel structure and the parameters of the cooling liquid, which have a major impact on the thermal behavior, are complicated and hard to be well understood. In this paper, we characterize the influence of these parameters on the steady-state temperature profiles of the dies in 3D-IC. The results presented in this paper are expected to offer help for the development of thermal design guidelines for 3D-IC with microchannel cooling.

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The physical thermal model

The physical thermal model of the 3D-IC is shown in fig. 1, where fig. 1(a) shows the 3D-IC without the microchannel cooling, while fig. 1(b) shows the 3D-IC with the integrated microchannel cooling.

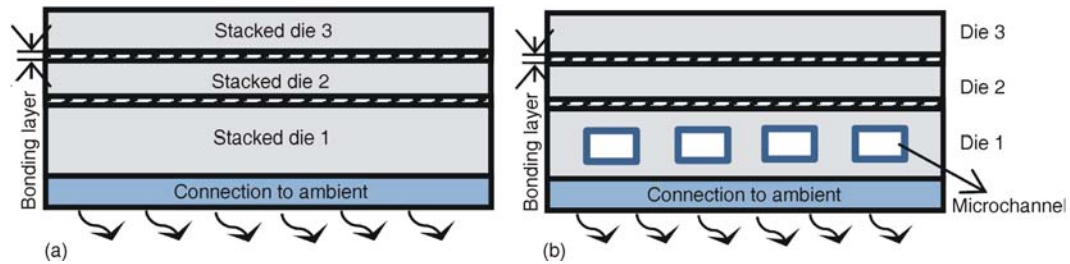


Figure 1. The 3D-IC model

The 3D-IC are composed of multiple stacked dies interconnected using through-silicon vias, while the number of devices that can be integrated within the system is limited as [8]:

$$\frac{\alpha N_G E}{t_{pd}} g \Delta T \quad (1)$$

where N_G is the number of gates that can be integrated within a system with a clock period t_{pd} , g – the average thermal conductance, ΔT – the temperature gradient between the dissipating elements and the ambient air, E – the energy dissipation, α – their activity rate. Heat flow in the 3D-IC is governed in a control volume of a solid that with the isotropic thermal conductivity by the following equation [11]:

$$C_v \frac{dT}{dt} = (k \nabla^2 T) - \dot{q} \quad (2)$$

where C_v is the volumetric specific heat of the material, T – the temperature of the control volume, k – the thermal conductivity of the material, \dot{q} – the volumetric rate of generation of the heat inside the volume. In the microchannel cooled 3D-IC, the energy conservation equation for heat transfer in a control volume of the liquid can be written:

$$C_v \frac{dT}{dt} = (k \nabla^2 T) - C_v \bar{u} T + \dot{q} \quad (3)$$

When compared to eq. (2), the previous equation contains an added term on the left hand side, where \bar{u} is the velocity of outflow of the fluid at the surface of the control volume.

Experimental results

As shown in fig. 1, the 3D-IC model that we use to study has three dies, which integrates four microchannels in die-1. The microchannels have the same structure, where the height and width are 1.0 mm and 2.0 mm, respectively. The die-1, die-2, and die-3 that have the same thermal conductivity of 120 W/mK are assumed to be 10 mm × 10 mm × 3 mm, 10 mm × 10 mm × 2 mm, and 10 mm × 10 mm × 2 mm, respectively.

The two bonding layers are both 10 mm by 10 mm by 0.5 mm with the same thermal conductivity of 2 W/mK. From the top view, the heat generations of the three dies are shown in fig. 2, they are $1.0 \cdot 10^9$ W/m³ (Position: 1 mm < x < 3 mm, 1 mm < y < 3 mm, and 1 mm < z < 3 mm), $2.0 \cdot 10^9$ W/m³ (Position: 4 mm < x < 6 mm, 4 mm < y < 6 mm, and 4.5 mm < z < 6 mm), and $3.0 \cdot 10^9$ W/m³ (Position: 7 mm < x < 9 mm, 7 mm < y < 9 mm, and 7.5 mm < z < 9 mm).

5.5 mm), $1.0 \cdot 10^9 \text{ W/m}^3$ (Position: $7 \text{ mm} < x < 9 \text{ mm}$, $7 \text{ mm} < y < 9 \text{ mm}$, and $8 \text{ mm} < z < 9 \text{ mm}$), respectively. At the bottom of the bottom-most die, the convective heat transfer coefficient is set to be $1000 \text{ W/m}^2\text{K}$, while the other side surfaces are assumed to be adiabatic.

Case (1). The impact of the introduced microchannels

In this case, we study the impact on temperature rise as the microchannels are introduced in the 3D-IC. Figure 3(a) shows the temperature curves along the y-direction in the three different dies of the 3D-IC that without microchannel cooling. When the microchannels are introduced, the temperature curve is plotted in fig. 3(b). Compared with fig. 3(a), we find that the temperature has about 24% decline when the microchannels are introduced.

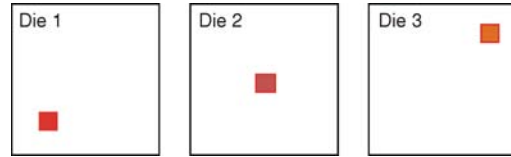


Figure 2. Heat generation distribution in each die from the top view

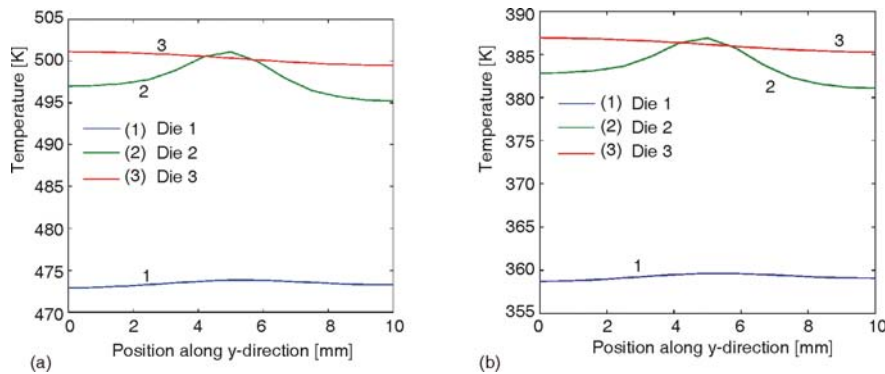


Figure 3. Influence of the microchannel cooling on temperature rise in 3D-IC

Case (2). The structure of the microchannel

In this case, we change the structure of the microchannels to find out the impact on the temperature rise, that is, taking the surface areas of the microchannel as invariant while changing both the width and height of the microchannel to be 1.5 mm. As shown in fig. 4, the temperature of the die-1 along the y-direction decreases a little when the microchannel structure is changed.

Case (3). Velocity of the cooling liquid

In this case, we study the influence of the cooling liquid velocity on temperature rise via increasing the velocity by 2 and 4, respectively. Figure 5 shows the temperature curves of the

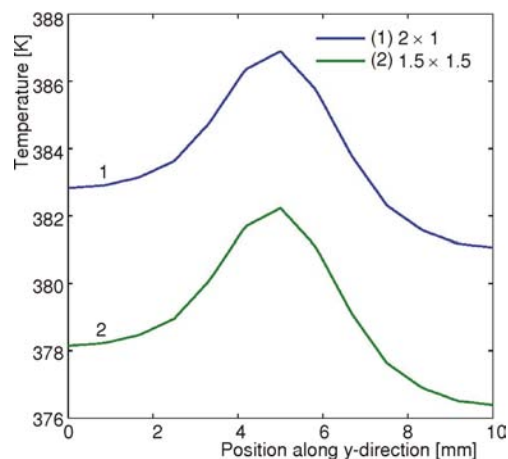


Figure 4. Influence of the microchannel structure on temperature rise in 3D-IC

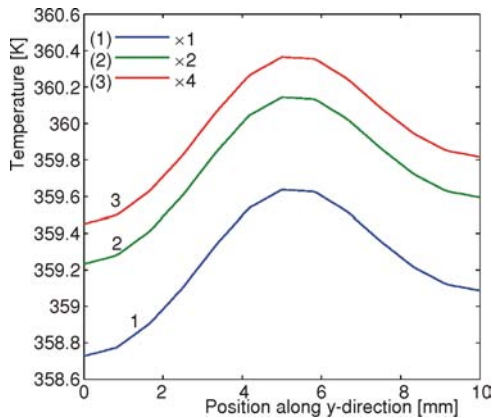


Figure 5. Influence of velocity of the cooling liquid on temperature rise in 3D-IC

different velocities in die-2 along the y-direction. It can be found that the temperature increases as the velocity increases.

Conclusion

In this paper, we studied the influence of the microchannel structure and the parameters of the cooling liquid on the thermal behavior of the 3D-IC. We analyzed the impact of the microchannel, the microchannel structure, and the velocity of the cooling liquid on temperature rise of 3D-IC. This paper is expected to aid in developing temperature characterization and prediction tools for 3D-IC with microchannel cooling. In addition, this paper may also be helpful in the characterization of various thermal management strategies being proposed for 3D-IC with microchannel cooling.

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