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Experimental study on substrate with hierarchical nested channels for thermal interface resistance control

Xiaobing Luo,[1,2,a)] Huai Zheng,[1] Minglu Liu,[3] and Sheng Liu[2,3]
[1]*School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*
[2]*MoEMS Division, Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China*
[3]*School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China*

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Thermal interface resistance is an important parameter for the thermal management of electronics packaging. In order to reduce thermal interface resistance, hierarchical nested channels were designed and fabricated on the surfaces of aluminum and copper sheets. Experiments were conducted to measure the thermal interface resistance of the sheets. A sequence of experimental results revealed that thermal interface resistance of the sheets with hierarchical nested channels is 2−3 times larger than that of the original flat sheets without the channels, which is contrary to the experimental objective. A comprehensive experimental analysis was presented to explain the phenomenon. It is found that the roughness of contact interface plays a key role. In the reported references, the thermal interface material composed of metal particles is easy to form particle stacking in the smooth contacting surface, therefore, the hierarchical nested channels can effectively reduce the particle stacking and the corresponding thermal interface resistance. However, in the present experiment samples, the surface roughness is larger than 10 μm, the phenomenon of particle stacking is difficult to occur, the hierarchical nested channels cannot perform well for decreasing particle stacking and thermal resistance. Otherwise, the hierarchical nested channels increases the bulk thermal resistance because of the replacement of the high thermal conductivity metal material with thermal greases that have relatively low thermal conductivity. © *2011 American Institute of Physics*. [doi:10.1063/1.3586252]

I. INTRODUCTION

Electronic products are usually structured by connecting multilayer components, and the heat flux generated by electronic chip goes through several thermal interfaces before dissipating into the surrounding environment. As chip power density increases, heat dissipation becomes a significant factor to affect the performance and reliability of the electronic products. An inevitable result for electronic packaging is that the large contacting resistance consumes up a large amount of the total heat budget, and in some devices, it can be up to 20%−50%.[1] Therefore, how to reduce thermal contact resistance becomes one of the most critical problems in thermal management of electronic packaging.

Thermal interface materials (TIM), such as thermal greases, thermal adhesives, and solders, are usually used to decrease the thermal interface resistance and reduce the air gaps between the contact interfaces by conforming to the rough and uneven mating surfaces.[2] The bulk thermal conductivity of the thermal interface material, the contact area of the thermal interface material and solid layer, and the bondline thickness (BLT) are the main factors which determine the thermal interface resistance.

Research was conducted to improve the bulk thermal conductivity of the commercial thermal interface material by mixing particles with higher thermal conductivity. Xu *et al.*[3] embedded sliver nanowire arrays inside polycarbonate template and obtained thermal interface material with a high intrinsic thermal conductivity of 30.3 $\mathrm{Wm^{-1}\,K^{-1}}$. Xu and Fisher[4] further developed a higher thermal conductivity thermal interface material by synthesizing carbon nanotube (CNT) arrays directly on silicon wafer using plasma-enhanced chemical vapor deposition, and achieved a minimum thermal interface resistance of 5.2 $\mathrm{mm^2\,KW^{-1}}$. With the increasing of particle volume fraction, the bulk thermal conductivity of a particle-filled thermal interface material increases exponentially.[5] However, the use of CNT in TIM dramatically increases the cost of thermal interface materials. Furthermore, with the increase of the particle volume fraction, the viscosity of thermal interface material exponentially increases, which prevents the formation of the thin bondline thickness (BLT).[6] Some researchers tried to find alternative ways to reduce the thermal interface resistance. Lo *et al.*[7] proposed a processing scheme to assemble the fins on the contact surfaces in order to extend the effective surface for heat conduction. They also developed thermal analysis model to prove the scheme theoretically and optimize the fin shapes and sizes. In the theory, the heat conduction surface was only taken into account, ignoring the influence of the BLT and voids on the thermal interface resistance. Linderman *et al.*[8] proposed a technology to reduce thermal interface resistance using hierarchical nested surface channels on

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[a)] Electronic mail: Luoxb@mail.hust.edu.cn.

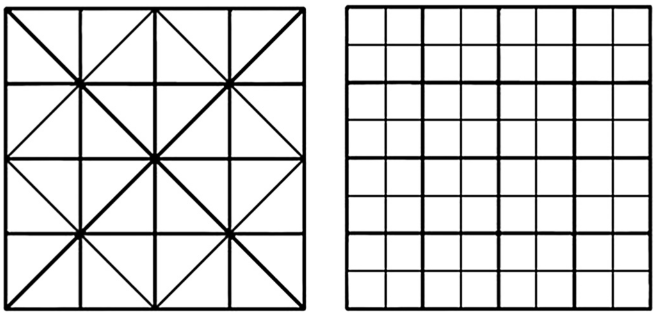

FIG. 1. Two kinds of hierarchical nested channel designs, design 1 (left design), design 2 (right design).

the contact surface, which can control the particle stacking during bondline formation. Based on such a method, thin bondline thickness (BLT) with thermal interface material filled with high particle volume fraction can be formed. They obtained thermal interface resistance as low as 2 mm^2KW^{-1} for thin bondline (< 5 μm).[8,9] Brunschwiler[10] also developed a scheme of hierarchical nested channels that can form the bondline rapidly for high thermal conductivity interface materials from higher volumetric particle loadings.

The hierarchical nested channels were fabricated on aluminum and copper sheets surfaces to reduce thermal interface resistance, and the experimental measurements of thermal interface resistance were conducted. Two types of hierarchical nested channels were processed on the surfaces of aluminum and copper sheets, respectively. Then, thermal interface resistance were measured and compared by the original sheet without the channels. It is found that the thermal interface resistance of the original sheet is 2−3 times less than those with channels. The result contradicts that described in Ref. 9. A theoretical analysis about this contradiction was consequently conducted.

II. FABRICATION AND MEASUREMENT

A. Fabrication

The metal sheets in the experiments were fabricated. The size and layout of the hierarchical nested channels are shown in Fig. 1. This figure shows two kinds of designs with different hierarchical nested channels. In both designs, the metal sheets are with 20 mm length, 20 mm width, and 1 mm thickness. Thick lines represent the first-level hierarchy channel with 200 μm depth and 300 μm width, thin lines means the second level channel with 100 μm depth and 300 μm width. The above two designs were fabricated on the surfaces of aluminum and copper sheets, respectively, thus four samples were fabricated. For comparison convenience, two samples by aluminum and copper sheet without any channels were also prepared. Finally, all the test samples are shown in Table I.

B. Experimental measurement setup

The experimental setup for measuring the thermal interface resistances of the samples is shown in Fig. 2. The whole system contains four important parts: pressure adjustment part, temperature and loading measurement part, heating and cooling part, and temperature insulation subsystem. The pressure adjustment part is also called a loading cell. It includes a screw device, which provides contact pressure by whirling the turn plate. A disk is fixed under the screwed bar. Since the force of the turning screw depends on manual operation, the range of the pressure can be adjusted from ∼0 to 3 MPa.

TABLE I. Experimental samples.

Samples	Sheet material	Channel design
1	Aluminum	No channel
2	Aluminum	Design 1
3	Aluminum	Design 2
4	Copper	No channel
5	Copper	Design 1
6	Copper	Design 2

As shown in the right part of Fig. 2, the two aluminum bars are used for the heat flux meter. The heights of the upper and lower bars are 100 and 75 mm, respectively, and the length and width of both bars are 20 mm. The K type thermocouples locate on both bars, and have a distance of 20 mm from each other. The temperatures are measured by digital computer-based data acquisition systems. The loading cell's measured weight can be transferred as electronic signals, and displayed in the display instrument.

There are three cartridge heaters inserted in an aluminum block for heating supply. It is powered by a 40 W heater through a variable transformer controller. The heater contacts directly with aluminum bar. To prevent heat loss, cotton is used for insulation. The rest of the space between the heater and the cotton are filled by foam material. The heating area is adjustable, and a more uniform heat is achieved. To take heat away from the two aluminum bars, a cold plate is placed on the upper aluminum bar. Heat-conducting cream has been smeared on the upper surface of the aluminum bar to enhance heat transfer. The cold plate is cooled by the water cooling system.

C. Test principle

Due to the thermal interface resistance between two aluminum bars, there exists a big temperature difference between two aluminum bars' interfaces. Thermal interface

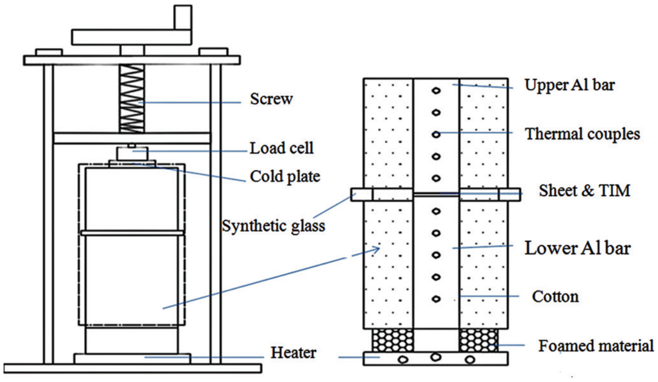

FIG. 2. (Color online) Experimental setup schematic.

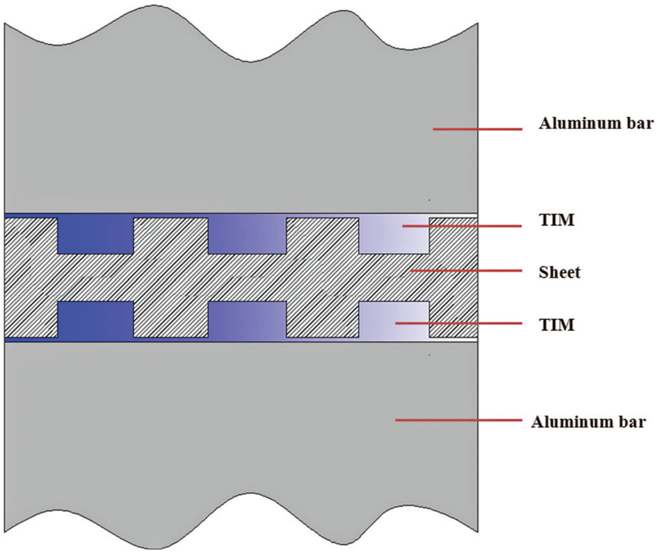

FIG. 3. (Color online) Diagram of interface section.

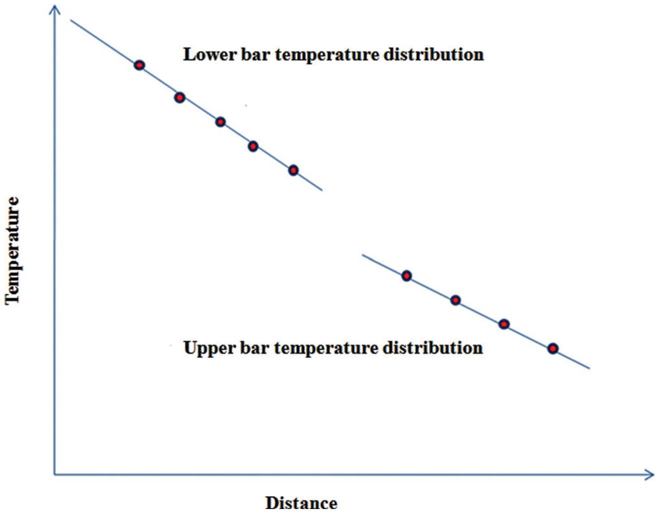

FIG. 4. (Color online) Temperature distributions of the two aluminum bars.

resistance is characterized by the resistance to heat flux on the interfaces of the two aluminum bars. The layout of thermal interface material and sheet between two aluminum bars is shown in Fig. 3. It can be seen that the thermal interface resistance includes four thermal contact resistances and three bulk thermal resistances. It is calculated through the temperature difference of the two contact surfaces divided by the heat flux through the interfaces.

The heat insulation in this study was through cotton, which was wrapped around the two aluminum bars along radical direction to prevent heat loss from the radial direction. Thus, heat transfer in the aluminum bars could be simplified to be one-dimensional. In this experimental setup, the two bars were not only utilized to fit the temperature on the interfaces but also for the heat flux meters. Nine thermocouples were inserted into the holes in the aluminum bars to measure the temperature distribution. The temperature gradients in the aluminum bars then could be calculated using the method of the least squares. According to Fourier's law, the one-dimensional heat-transfer rate can be calculated as

$$q = -\lambda \times \frac{\partial t}{\partial x}, \tag{1}$$

where λ is the thermal conductivity of the aluminum bar. After heating the bars ~2 h, stable temperatures can be obtained from the thermocouples. The temperature data is fitted by the least square multiplication. The $\partial t/\partial x$ is the temperature slope of the bar. According to Eq. (1), the heat flux through each bar can be calculated, and finally the averaging heat flux q can be obtained for thermal contact resistance computation.

As shown in Fig. 4, the lower line is the fitting line of the four temperature points of the upper bar, and the upper line is the fitting line of the five temperature of the lower bar. The upper surface temperature t_1 and the lower surface temperature t_2 can be obtained. Therefore, the thermal contact resistance R can be calculated by the following Eq. (2), where the unit of R is $\mathrm{m}^2\ \mathrm{KW}^{-1}$.

$$R = \frac{t_2 - t_1}{q}, \tag{2}$$

based on the principle introduction, to keep good measurement accuracy for the present test setup, the one-dimensional thermal conduction through the axis of the two bars is very important. To obtain this target, thermal insulation around the bars is necessary.

To reduce the measurement effect of the test apparatus on the TIM and thermal interface resistance, some factors of the apparatus such as loading pressure, temperature setup of temperature control unit and heat flux of the heater should be optimized according to the real application situation. Especially for the loading pressure, it must be kept the same as the real application so that the effect of the test method on TIM and thermal interface resistance is little.

D. Experimental uncertainty

The experimental uncertainty is caused by system bias and reproducibility of the tester. Figure 5 shows the temperature distribution of the upper aluminum, it proves that the experimental setup can keep good one dimensional thermal

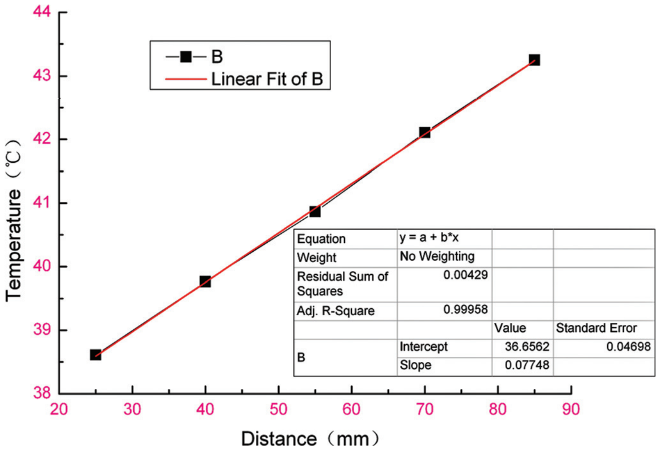

FIG. 5. (Color online) Temperature distribution of the upper aluminum bar.

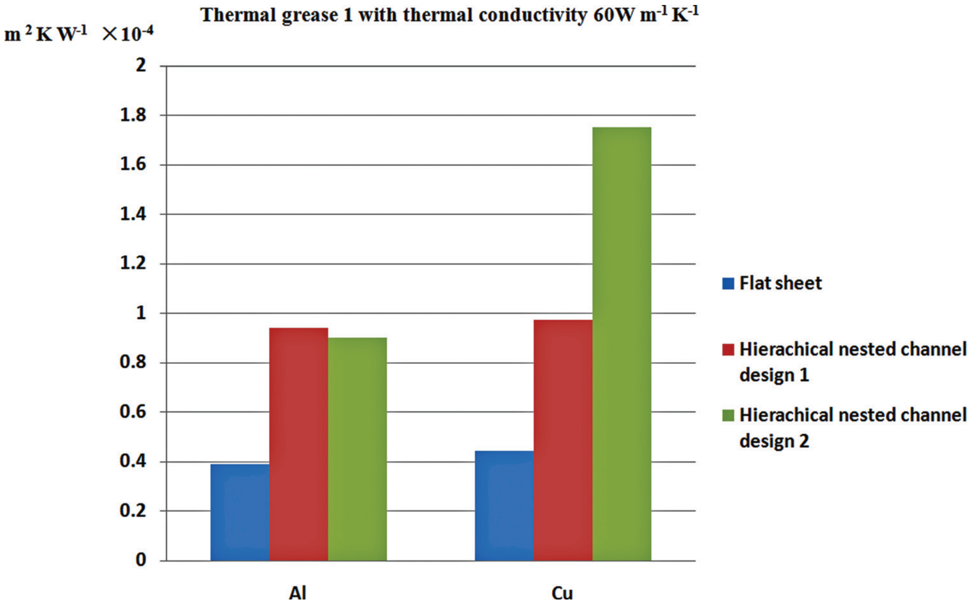

FIG. 6. (Color online) Thermal interface resistances under different cases when using thermal grease 1 as TIM.

conduction. The experimental setup had been used to measure thermal conductivity of aluminum and copper. It is found that the system bias is smaller than 1×10^{-5} m^2 KW^{-1}.

Reproducibility tests were conducted under different operation conditions. The measurement for thermal interface resistance of the same sample was repeated many times. It is found that the reproducibility is smaller than 1×10^{-5} m^2 KW^{-1}.

Actually, the difference of thermal interface resistance between flat sheet and sheets with hierarchical nested channels is more important than the absolute value of thermal interface resistance, the system bias comparably does not have important effect for the final conclusion.

III. EXPERIMENTAL RESULT AND DISCUSSION

In the experiments, the pressure of the interface between sheet and bars always keeps a constant value 0.375 MPa. The measurement of thermal interface resistance for each sheet was conducted several times. Two kinds of commercial thermal greases were applied as thermal interface materials. Their thermal conductivities are about 60 and 1.5 Wm^{-1} K^{-1}, respectively. The thermal interface resistances of the three aluminum sheets and three copper sheets using the two thermal greases are shown in Fig. 6 and Fig. 7, respectively.

Figure 6 shows the thermal interface resistances of three cases of designs when using thermal grease 1 whose thermal conductivity is 60 Wm^{-1} K^{-1}. It can be seen that when the

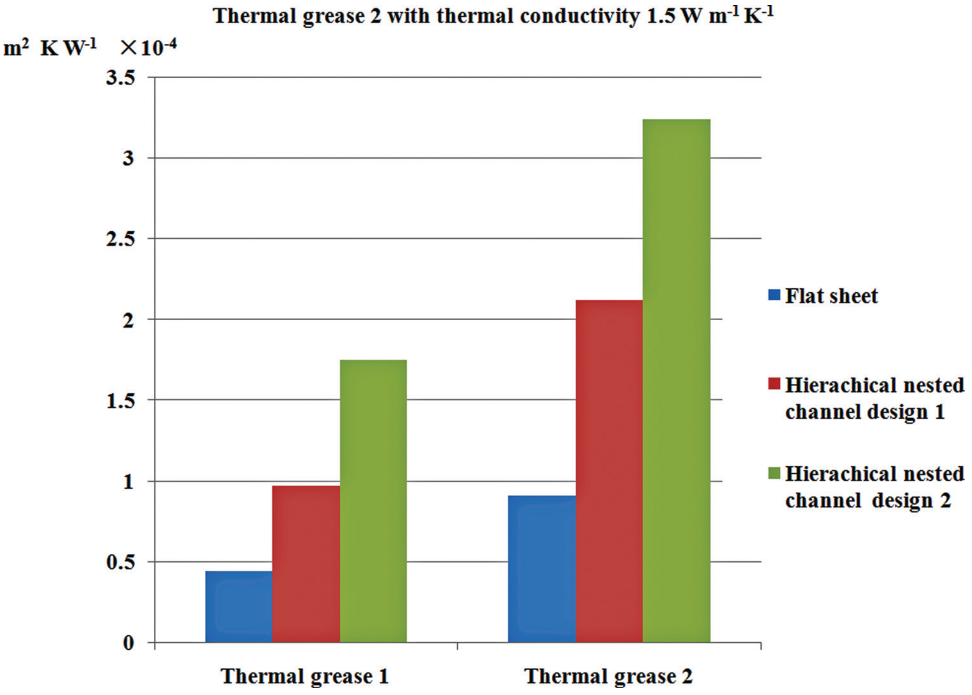

FIG. 7. (Color online) Thermal interface resistances when using thermal grease 2 as TIM.

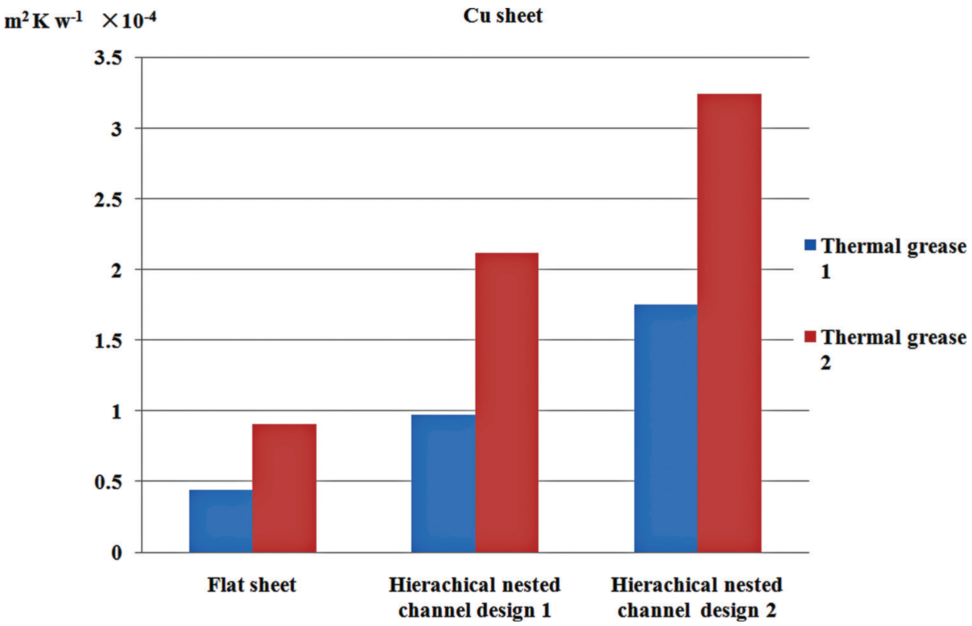

FIG. 8. (Color online) Thermal interface resistances under different cases when using both thermal greases as TIM.

sheet is made of copper, the thermal interface resistance with hierarchical nested channel design 2 is the largest. When the sheet is made of aluminum, the thermal resistances under two designs are nearly the same. The thermal interface resistance of flat sheet is the smallest under any cases. Figure 7 shows the same trend when thermal grease 2 with thermal conductivity 1.5 $\mathrm{Wm^{-1}\ K^{-1}}$ was used as TIM. Figure 8 shows the thermal interface resistances under different cases when using both thermal greases as TIM. It can be found from Fig. 8 that the thermal interface resistances using thermal grease 2 as thermal interface material is larger than that using thermal grease 1 as thermal interface material under any cases. This is due to the fact that thermal conductivity of thermal grease 2 is much smaller than that of thermal grease 1. When the other conditions are the same, the bulk thermal resistance of thermal grease 2 is much larger than that of thermal grease 1. Comparing the thermal interface resistance of flat sheet with those of sheets with hierarchical nested channel design 1 and design 2, it can be found that thermal interface resistance of flat sheets is 2−3 times smaller than those of the sheets with hierarchical nested channels either for copper sheet or aluminum sheet. The result is in contradiction with the conclusion described in Refs. 8 and 9, which is totally different from our experimental objective. For this contradiction, we found that it is caused by the surface roughness difference of the test samples with those in Refs. 8 and 9. Figure 9 shows the surface roughness of flat copper sheet measured by digital microscope. From Fig. 9, it can be seen that distance between the highest and the lowest surfaces of flat copper sheet is 10.5 μm.

In Refs. 8 and 9, the surface roughness of the chips is smaller than 1 μm, which is much smaller than that in our experiments. The size of particle in commercial thermal interface material ranges from 2 to 10 μm. Thus, the size of particle in thermal interface material is larger than the roughness of chip surface but smaller than roughness of aluminum and copper sheets. To explain the relation between particle size and surface roughness clearly, Figs. 10 and 11 were drawn. Figure 10 shows the particle distribution on the interfaces of smooth flat sheet versus smooth sheet with hierarchical nested channels during squeezing process. This figure shows the situations in Refs. 8 and 9. Figure 11 shows the particle distribution on interface of rough flat sheet versus rough sheet with hierarchical nested channels during squeezing process. This situation is the same as that in the present experiments. As shown in Fig. 10(b), when the particle size

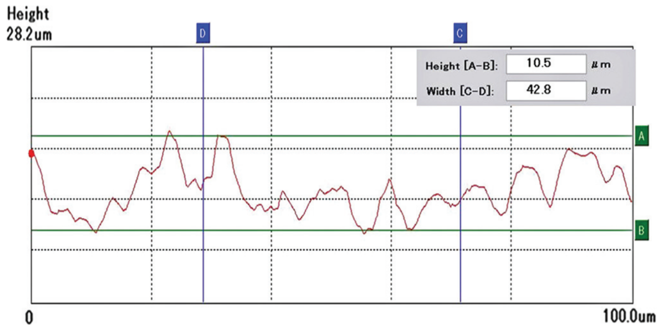

FIG. 9. (Color online) Surface roughness of flat copper sheet measured by digital microscope.

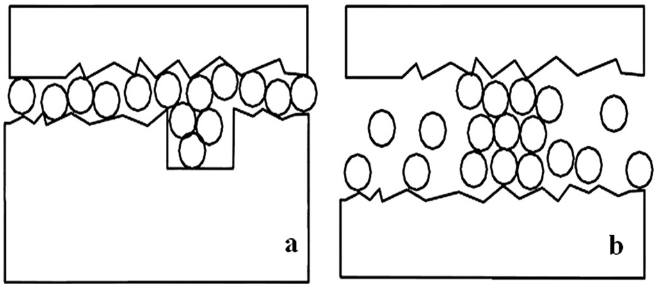

FIG. 10. Particle distribution on interface of smooth flat sheet vs smooth sheet with hierarchical nested channels during squeezing process: (a) smooth sheet with hierarchical nested channels; (b) smooth sheet without hierarchical nested channels.

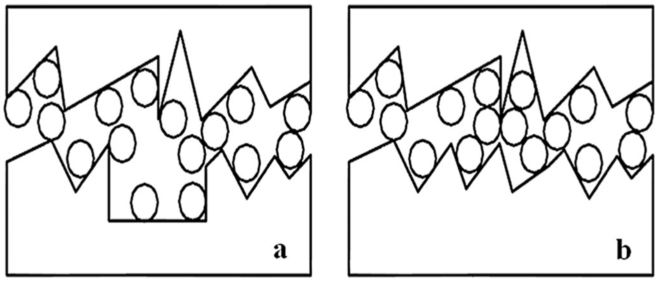

FIG. 11. Particle distribution on interface of rough flat sheet vs rough sheet with hierarchical nested channels during squeezing process: (a) rough sheet with hierarchical nested channels; (b) rough sheet without hierarchical nested channels.

is larger than the roughness of surface, thermal interface material results in particle stacking during squeezing process. When the hierarchical nested channels were fabricated as shown in Fig. 10(a), the hierarchical nested channels can prevent the big particle stacking and forming thinner bondline thickness on smooth chip surface, therefore, the thermal interface resistance will be decreased. However, for the present experiments on the aluminum and copper sheets, different with that shown in Fig. 10, the phenomenon of particle stacking does not exist in squeezing process since the roughness of sheet is larger than the size of particle, as shown in Fig. 11.

For both cases shown in Fig. 10 and Fig. 11, thermal interface resistance between two adjacent surfaces contains bulk thermal resistance of thermal interface material and thermal contact resistances. Hierarchical nested channels on relative smooth surface can prevent the particle stacking as shown in Fig. 10(a), and also reduce bulk thermal resistance of thermal interface material due to the thinner bondline thickness. As a drawback, the hierarchical nested channels filled with low thermal conductivity material will replace high thermal conductivity sheet material. Thus, it results in an additional bulk thermal resistance in comparison to the original flat sheet. Because the thermal interface material with high particle loading has high thermal conductivity, the additional bulk thermal resistance is very small. So the total thermal interface resistance will decrease when making channels on the very smooth sheet.

However, for the present aluminum and copper sheet cases shown in Fig. 11, the particle stacking is difficult to form because of the fact that the size of particle is smaller than the roughness of the inter surface. Hierarchical nested channels are not useful for reducing the bondline thickness. Otherwise, the additional bulk thermal resistance, as shown in Fig. 11(a), produced from that the metal sheet with high thermal conductivity being replaced by the thermal interface material with low thermal conductivity, will increase the thermal resistance compared with the case as shown in Fig. 11(b). Based on the above discussion, we also can explain the phenomena shown in Figs. 6–8. In Figs. 6 and 7, thermal interface resistance of sheet with hierarchical nested channel design 2 is larger than that of sheet with hierarchical nested channel design 1 when the other conditions are the same, which is due to the fact that the volume of channel in design 2 is larger. In Fig. 8, when using the thermal grease with relative higher thermal conductivity, the bulk thermal resistance increases less than that using thermal grease 2, when the other conditions are the same, the final thermal interface resistances for using thermal grease 1 will be smaller than that using thermal grease 2.

IV. CONCLUSIONS

In order to reduce the thermal interface resistance, hierarchical nested channels were fabricated on surfaces of aluminum and copper sheets. The experiments for measuring thermal interface resistance were conducted using self-designed setup. The results indicate that thermal interface resistance of sheets with hierarchical nested channels increases, which is contrary to our experiment objective and conclusions in Refs. 8 and 9. Through analysis, it is found that the effect of hierarchical nested channels is influenced by the relationship of surface roughness with particle size in thermal interface material. As the surface roughness is larger than the size of the particles filled into thermal interface material, hierarchical nested channels cannot reach the aim for reducing thermal interface resistance.

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