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Experimental Investigation on Composite Phase-Change Material (CPCM)-Based Substrate

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Many high-power electronic devices such as high-power light-emitting diodes and aerial devices work intermittently. If some of the heat generated by the chips could be stored in the thermal storage medium during the working time and then be released to the ambient in the nonworking time, the heat dissipation load of the heat sinks could be diminished and a better thermal characteristic could be achieved. Inspired by this idea, we proposed a thermal storage substrate and investigated its thermal storage properties by experiment in this study. First, the composite phase-change material (CPCM) was prepared as the thermal storage medium. Second, the thermal and phase-transition properties of the CPCM were studied through differential scanning calorimeter tests. Third, the thermal conductivity of the CPCM was measured for the analysis of thermal performance. Afterward, the CPCM-based substrate was fabricated and several experiments were conducted to examine its thermal storage performance. The results showed that the thermal storage substrate could store the heat, as much as 55,773.80 J, which accounts for 32% of the heat generated by the heat source approximately. With so much heat stored in the CPCM, the temperature of the heat source went up much more slowly. To accelerate the heat conduction inside the CPCM, five aluminum pillars were added into the substrate. As a result, the temperature of the heat source and the substrate wall decreased by 3.5°C and 4.5°C, respectively.

INTRODUCTION

With rapid development of electronic technology, the integration of electronic devices escalates. The input power of electronic devices grows, while the packaging size tends to be smaller. Consequently, the heat flux density increases sharply. Nevertheless, some high-power electronic devices have the working characteristic of intermittence, such as high-power light-emitting diode (LED) road lamps and aerial devices. Such devices always have a relatively short working time but produce high heat flux during the working time. If the heat cannot be removed in a timely manner, the chips, and even the whole devices, may fail to work. The thermal management of such high-power electronic devices has become a bottleneck that restricts their further development. Therefore, how to dissipate the high heat flux generated in a short time becomes challenging work for both the researchers and engineers.

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One possible idea is collecting some amount of the heat into the substrate when the electronic devices work, and then dissipating the heat to the ambient in the nonworking time. In this way, the nonworking time of the electronic devices could be utilized and the average heat dissipation load could be alleviated. The latent heat storage with phase-change material (PCM) has been investigated as an alternative passive thermal management solution in these years [1–6]. During the phase-change process of PCM, the heat can be absorbed greatly as large latent heat, and meanwhile the temperature stays stable. For these characteristics, the PCM could help to store the heat generated in a short working time, and release heat during the nonworking time. If such PCM-based substrate can be fabricated and applied, the electronic device can survive the temporary impact of the high-density heat flux. However, there are few mature PCM-based applications currently. One of the most important reasons is that there are few suitable PCMs. Among the PCMs, paraffin is regarded as the most promising one because of its advantages, such as high latent heat of fusion, wide option of the appropriate melting temperature, approximately constant melting temperature, and stable chemical and physical properties [7]. But the thermal conductivity coefficient of paraffin is generally quite low, and hence the heat cannot be stored in the paraffin quickly. To enhance heat transfer property inside the paraffin PCM, lots of investigations have been attempted, including dispersing the particles with high thermal conductivity into the matrix [8, 9], impregnating high-thermal-conductivity porous materials [10, 11], and adding metal structures with different configuration, such as pin/plate fins, in the PCMs [12–15]. Among these methods, the impregnation with expanded graphite is especially popular because of the advantages of its properties such as low density, high thermal conductivity, and good compatibility with the paraffin [16, 17]. In these literature reports, the researchers added different heat transfer enhancers inside the PCM with different processes to obtain the composite phase-change materials (CPCMs), and the thermal properties and heat storage performance of the CPCMs were studied. However, when applied in the thermal management of electronic devices who work intermittently, the thermal performance of the CPCMs was studied rarely. Besides, in previous studies, the heat transfer inside the PCM was generally enhanced with only one kind of enhancer, and few studies attempted to enhance the heat transfer inside the PCM with two different enhancers simultaneously.

In this study, inspired by the property of phase-change material, we proposed and fabricated the paraffin/expanded graphite CPCM-based substrate for thermal management of electronic devices who work intermittently and its thermal storage performance was also investigated. In addition, to improve the thermal management performance of the substrate, the heat transfer inside the substrate was enhanced with both expanded graphite and pillar fins added into the paraffin.

In this paper, the paraffin/expanded graphite CPCM was prepared through impregnating the paraffin into the expanded graphite. The thermal properties and phase transition characteristics of the CPCM were studied by means of a differential scanning calorimeter (DSC). To examine the heat storage performance of the CPCM-based substrates, experiments were conducted under the conditions of insulation and no-insulation with different heating power. Meanwhile, the amount of heat stored in the CPCM was calculated theoretically and experimentally, and analysis was done by accounting for the heat of the system. To enhance heat transfer properties inside the substrate, aluminum pillar fins were added into the substrate and experimental comparisons between the substrates with and without pillar fins were conducted.

FABRICATION OF CPCM AND THERMAL TEST

Before the preparation of the CPCM, the raw materials, namely, the technical-grade paraffin and expandable graphite, were purchased. The physical parameters of the expandable graphite are as follows: average particle size 270 μm, expansion ratio 200 ml g^{-1}, sulfur content below 0.02%, expansion temperature higher than 900°C. The melting temperature T_m of the paraffin is 56–58°C. First, the expandable graphite was placed in a vacuum oven and dried at 70°C for 12 h. Then a steel crucible that contained about 2–3 g of the dried expandable graphite was put into a muffle furnace, and a subsequent heat treatment was held at 900°C for 40 s [17]. After these processes, we could obtain the expanded graphite. In the following process, the paraffin was cut into small pieces and melt in a stainless-steel container at 80°C. Afterward, the expanded graphite was put into the liquid paraffin to absorb the paraffin abundantly according to the mass percentage of 15% and 5%, respectively. The whole absorption was held in the oven, and the agitation was required to make sure of mixing completely. Finally, we got the paraffin/expanded graphite CPCM.

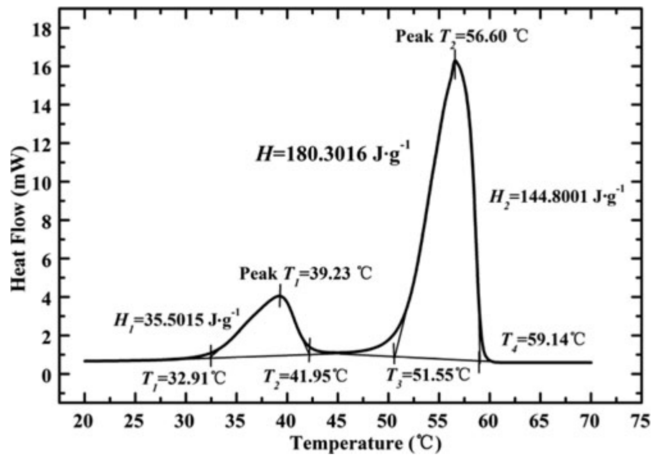

Figure 1 DSC test of paraffin.

To obtain the thermal characteristics of the paraffin and the composite material, the DSC test was conducted with the temperature rising rate of 5°C min^{-1}. The typical DSC curves of the pure paraffin are shown in Figure 1. The temperature and the heat flow are displayed on the abscissa and the ordinate, respectively, and vary along with the melting of paraffin. The DSC curves show that there exist two peaks of the heat flow, the main peak on the right and the minor peak on the left. With temperature increasing, the solid-solid phase transition process, which is the minor phase-change process, occurs first at 32.91°C, and the heat flow reaches the first peak value at 39.23°C. Then the main phase transition process begins when the liquid paraffin shows up at 48.79°C, and the heat flow arrives at the main peak when the temperature rises to 56.60°C; finally, the whole phase-change process ends at 59.14°C. Besides, as shown in Figure 1, the latent heat of the paraffin is 180.30 J g^{-1}, which is obtained by numerical integration of the area under the phase-change curves along the x-axis by the line.

Similar to the melting process of paraffin, the CPCM, in which the mass percentage of paraffin is 85%, also takes the two-phase transition process with two heat flow peaks, as shown in Figure 2. The minor peak starts at 32.85°C and reaches the top at 39.26°C, while the main peak starts at 50.65°C and reaches the top at 56.84°C. Comparing the two figures, it can be concluded that the phase transition temperatures of the CPCM are almost the same as those of the pure paraffin, and so are the other thermal characteristics. While the latent heat of the CPCM is

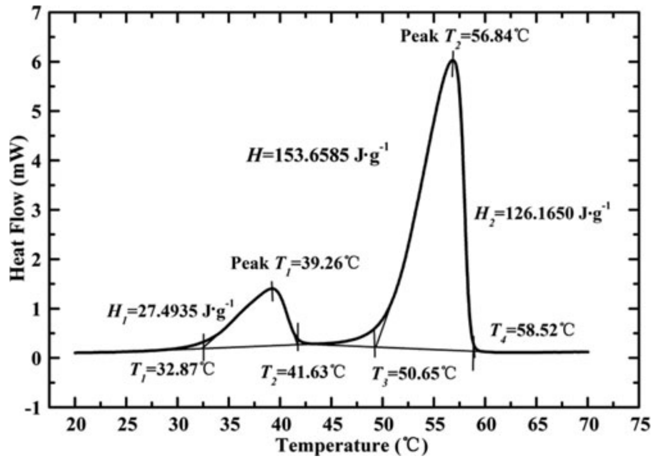

Figure 2 DSC test of the composite PCM.

153.66 J g^{-1}, it equals 85% of that of the paraffin. It is also equivalent to the value calculated by multiplying the latent heat of the pure paraffin (180.30 J g^{-1}) by the paraffin mass fraction (85.6%) in the CPCM. With the DSC test results, we conclude that the paraffin has stable chemical properties and keeps constant thermal properties such as melting temperature and latent heat when compounded with the expanded graphite. In order to obtain a relatively large quantity of latent heat and a substantial thermal conductivity coefficient, the CPCM with paraffin of 95 wt% is selected and studied in the following portions. Furthermore, the TC3000 Thermal Conductivity Tester (XIATECH, China) was utilized to test the thermal conductivity of the paraffin and the CPCM with paraffin of 95 wt%, and the results are as shown in Table 1. From the table, we can see that with the expanded graphite stuffed inside, the paraffin has a 524% increase of thermal conductivity, and when it melts, the thermal conductivity property becomes worse.

EXPERIMENTAL APPARATUS AND METHODS

In the experiment, the substrate (dimension of 108 × 88 × 54 mm^3 and weight of 0.541 kg) containing 266 g CPCM is set as the heat sink for the high-power electronic devices that work intermittently, and it is displayed in Figure 3. To investigate the thermal storage properties of the substrate for the thermal management of electronic devices adequately, different working conditions have been considered. During the experiment, different heat source working power was adopted and different insulation conditions of the substrate were employed. For the condition with minor heating power the experimental system was insulated, while for the condition with higher heating power the experimental system was exposed to the ambient.

Table 1 Thermal conductivity test of paraffin and CPCM

Material	Temperature (K)	Test voltage (V)	Thermal conductivity (W m^{-1} K^{-1})
Paraffin (solid)	301.54	1.5	0.25
Paraffin (liquid)	333.37	1	0.19
CPCM	309.46	2.5	1.56

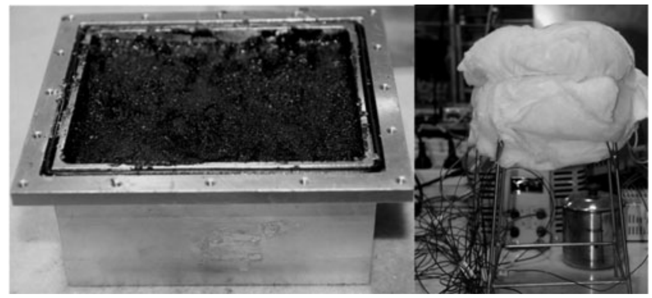

Figure 3 Pictures of the CPCM-based substrate (left) and the insulation effect of the cotton (right).

In the circumstance of insulation, the substrate was wrapped with adiabatic cotton as depicted in Figure 3. The schematic view of the experimental system was shown in Figure 4. The experimental setup mainly consists of the aluminum substrate with the CPCM inside, heat source module (dimension of 70 × 50 × 20 mm^3 and weight of 0.53 kg) at the bottom of the substrate, the power supply, and the data acquisition unit (DAQ). Because of the volume expansion of the CPCM when melted, some space above the CPCM inside the substrate was left for air.

The substrate was covered and sealed with a thin aluminum plate from the upper side through 16 screws. The temperature of the adiabatic cotton, the substrate, the heat source, and the ambient air was measured by K-type thermocouples (TCs) 1 to 14, for which the specific locations are displayed in Figures 4 and 5. The temperature signal captured by the Data Acquisition Instrument (Kethley 2700 Multimeter) was delivered to the computer to have the further analysis.

In the experiment without any insulation, the cotton was abandoned and the substrate was exposed in the ambient. The locations of the thermocouples except those stuck on the surfaces of the cotton are also clearly seen in Figures 4 and 5.

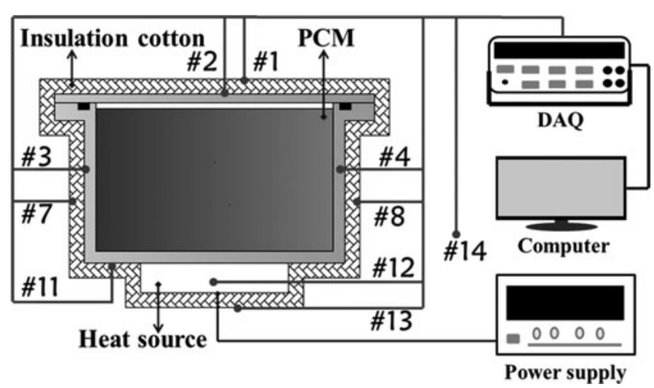

Figure 4 Schematic view of the experimental setup and location of the thermocouples (TCs) 1 to 14.

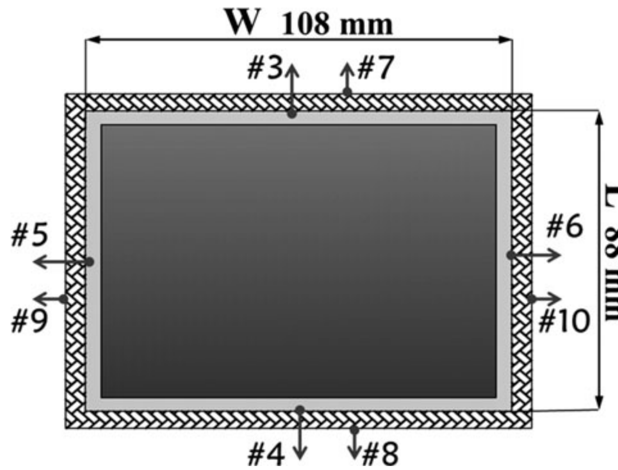

Figure 5 Location of the thermocouples (TCs) 3 to 10.

RESULTS AND DISCUSSION

Under Insulation Condition

In the experiment under the condition of insulation, the heating power of the heat source was 5 W. To seek for a good insulation effect, the adiabatic cotton was packed relatively thick and its outer surfaces were exposed to the ambient air to conduct the large-space natural convection. During the experiment, the average temperature of the ambient air was 26°C and the temperature signals were logged every 30 seconds. Because of the small difference between the temperatures of the four around-side walls of the substrate, we took their average temperature as the wall temperature. The approximate treatment was also applied to the adiabatic cotton. The temperature curves recorded by the thermocouples are displayed in Figure 6.

As indicated in the coordinate system of Figure 6, the temperature varies with the heating time. At the beginning, the initial temperature of the experimental system is the same as the ambient temperature, and then the temperature curves go up when the heat source works. First, the curves rise at a relatively fast speed until the heating time reaches 4 hours, and then there is a change on the elevating slope of the curves, and the curves become gentler until 9.33 hours. Afterward, the temperature curves recover an even faster speed than that in the first period. In accordance with the variation of the temperature curves, the working process of the CPCM-based substrate could also be divided into three stages, namely, the first stage of thermal storage before phase transition, the second stage of thermal storage during phase transition, and the third stage after phase transition, as shown in Figure 6. At the first and the third stages, the heat was mainly stored as sensible heat, while at the second stage the heat was mostly stored as latent heat, which had much bigger thermal storage capacity than the sensible heat. At the second stage, the average temperature rise rate is 1.313°C per hour, which is much slower than that at other stages. At the end of the first stage, the wall temperature of the substrate and the temperature of the heat source are 52°C and 54°C, respectively. Considering these factors and that the walls of the substrate are relatively thin, the coefficient of thermal conductivity of the aluminum plate is sufficiently high and the thermal insulation effect is good enough, and the wall temperature of the substrate and the temperature of inside the CPCM close to the wall are seen as the same. The approximation of the temperature is similarly applied to that at the end of the second stage when the temperatures of the heat source and the substrate reach 61°C and 59°C individually. Then we can see that the turning points of the substrate temperature curve have a good agreement with the solid–liquid transition temperatures of the paraffin, which are 51.55°C and 59.14°C, as shown in Figure 1.

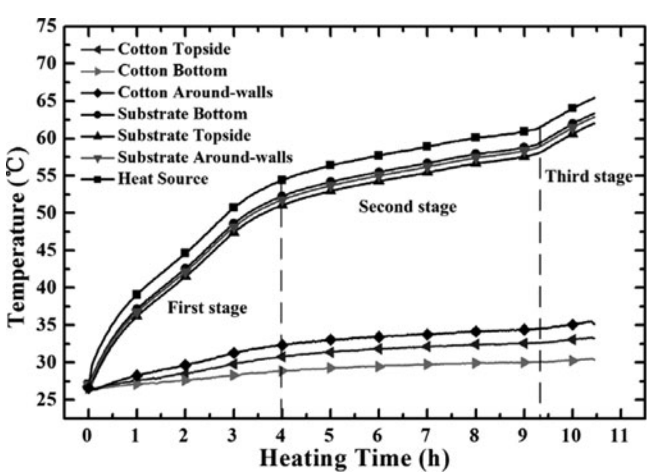

Figure 6 Temperature curves under the condition of insulation.

The temperatures of the cotton, measured at the top, the bottom, and the around-side wall, are also displayed in Figure 6. The temperature of the cotton rises within 10°C over the 10.5 hours during the experiment. In spite of the insulation by the cotton, a large quantity of heat dissipated to the environment through the outer surfaces of the cotton.

In order to obtain the accurate amount of the heat stored in the CPCM during the experiment, the heat distribution was calculated. For the experimental system shown, the heat dissipation load could be divided into three parts. One part of the heat was stored in the heat source module and the body of the substrate as the sensible heat. In this part, the assumption is made that the insulation cotton has poor heat absorption property and the heat stored in the cotton is neglected. Q_{heat} and Q_{sub} represent the heat stored in the heat source and the body of the substrate, respectively. One other part of the heat Q_{pcm} was absorbed in the CPCM as the sensible and latent heat when the phase transition took place. The other part was the heat Q_{con} dissipated to the environment through the outer surfaces of the adiabatic cotton. To obtain Q_{con}, the convective heat transfer coefficient h should be solved first. During this process, we took the empirical formula of the natural convection in the large space approximately. The equations are as shown in the following:

$$\mathrm{Nu} = \frac{hl}{\lambda} = c(\mathrm{Gr} \cdot \mathrm{Pr})^n \tag{1}$$

Table 2 Thermophysical parameters of the surfaces of the insulation cotton

Parameters	$\frac{L}{m}$	$\frac{t_w}{°C}$	$\frac{\theta_w}{°C}$	$\frac{t_m}{°C}$	$\frac{\lambda\times10^2}{W\cdot m^{-1}\cdot K^{-1}}$	$\frac{\nu\times10^6}{m^2\cdot s^{-1}}$	Pr	$\frac{h}{W\cdot m^{-2}\cdot K^{-1}}$
Around walls								
First stage	0.15	29.25	3.25	27.63	2.65	15.76	0.701	3.31
Second stage	0.15	33	7	29.5	2.67	16	0.701	4.01
Top side								
First stage	0.175	28.25	2.25	27.13	2.64	15.71	0.701	2.66
Second stage	0.175	31	5	28.5	2.66	15.85	0.701	3.24
Bottom								
First stage	0.175	27	1	26.5	2.64	25.60	0.702	1.08
Second stage	0.175	29	3	27.5	2.85	15.81	0.701	1.43

$$\mathrm{Gr} = \frac{g\beta\theta_w L^3}{\nu^2} \tag{2}$$

$$\Phi = Ah\Delta T \tag{3}$$

$$Q_{con} = \Phi \cdot t \tag{4}$$

$$Q_{in} = P \cdot t \tag{5}$$

In Eq. (1), n gets the value 0.25 both at the bottom and the around side of the cotton, while c gets the values 0.27 and 0.59 separately. When applied in Eq. (2), g takes the value 9.8 g m^{-2} while β takes the value 0.0033. In the calculation of Q_{con}, the wall temperature of the cotton, which was regarded as the characteristic temperature according to the appendix [18], was supposed to be constant and its value was taken as the average temperature of the initial and the ending temperature of each stage. With Eqs. (1) and (2) and the characteristic temperature, we can obtain the thermophysical parameters and the equivalent convective heat transfer coefficient h of various stages approximately, as shown in Table 2. Then the heat dissipated to the environment Q_{con} could be solved to be 87,968.31 J by Eqs. (3) and (4). With Eq. (5) we can obtain the input heat Q_{in}, 168,000 J.

By Eq. (6), the heat absorbed by the substrate and the heat source is calculated to be 15,541.34 J and 8716.86 J, respectively. During the calculation, the specific heat capacity C_p of the substrate and the heat source is 871 J kg^{-1} K^{-1} and 470 J kg^{-1} K^{-1} separately. According to the law of the conservation of energy and the results obtained earlier, we can get the experimental heat storage of the composite PCM based substrate 55,773.80 J by Eq. (7) with the heat stored in the insulation cotton neglected because of its poor heat absorption property:

$$Q = C_P m \Delta T \tag{6}$$

$$Q_{store}^{exper} = Q_{in} - Q_{heat} - Q_{sub} - Q_{con} \tag{7}$$

$$Q_{store}^{theory} = m_{pra} \times (T_1 - T_\infty \times C_p^{pra} + H) + m_{gra} \times T_4 - T_\infty \times C_p^{gra} \tag{8}$$

$$\eta = \frac{\left| Q_{store}^{exper} - Q_{store}^{theory} \right|}{Q_{store}^{theory}} \tag{9}$$

The theoretical heat storage of the substrate is acquired from Eq. (8). The theoretical heat storage can be divided into two parts in accordance with the components of the CPCM, the theoretical heat storage of the paraffin, and that of the expanded graphite. There are two stages in the heat storage of the paraffin, which includes the sensible heat storage process and latent heat storage process. For the expanded graphite, there is only the sensible heat storage process. In Eq. (8), T_1 is the temperature when the paraffin begins to melt and T_4 is the temperature when all the paraffin melts to liquid in the paraffin DSC test. The specific heat of the paraffin and the expanded graphite, C_p^{pra} and C_p^{gra}, are 2.7 J g^{-1} and 0.71 J g^{-1}, respectively. The qualities of the two constituents, paraffin and the expanded graphite, are described as m_{pra} and m_{gra}. With these parameters, we get the theoretical heat storage of the CPCM, 55,773.80 J, which accounts for 33.20% of the heat input by the heat source. Compared with the theoretical heat storage, the experimental error is 1.96% by Eq. (9).

Under Condition of No Insulation

In this experiment, the adiabatic cotton was abandoned and the whole experimental setup was exposed to the ambient air. The heating power of the heat source was added to 15 W. The temperature curves are displayed in Figure 7. Similar to the temperature curves shown in Figure 6, the rising slope of the temperature curves of the heat source and the substrate took apparent change at the time of 1.33 hours and 3.33 hours due to the melting characteristic of the paraffin. There had smaller rising trend of the temperature in the intermediate stage compared with the other stages because of the massive latent heat storage of the CPCM.

As shown in Figure 7, at the beginning of the second stage the temperature of the heat source was 62.5°C while the wall temperature of the substrate was 55°C, which was higher than the starting temperature of the main melting process of the paraffin. The main reason was that the heat could not be stored into the CPCM immediately because of the low thermal conductivity of

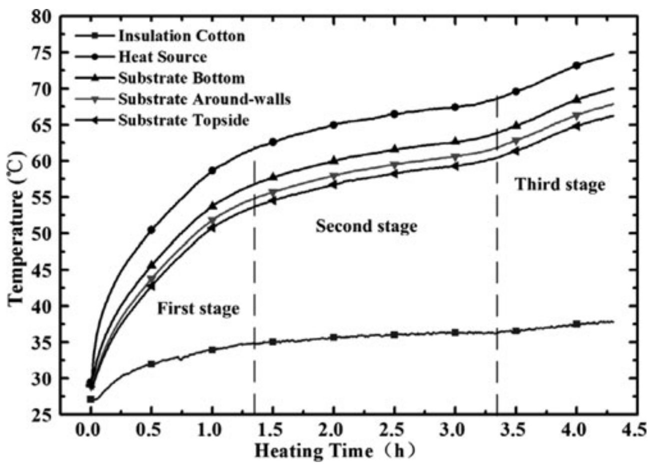

Figure 7 Temperature curves under the condition without any insulation.

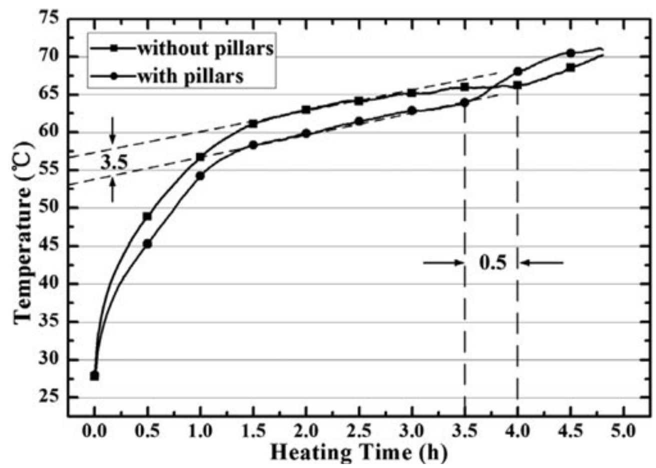

Figure 9 Comparison of the heat source temperatures.

the CPCM and the large amount of heat that had to be dissipated to the ambient air with a higher heat source temperature. Hence, measures should be taken to enhance the heat conduction inside the CPCM and diminish the thermal resistance between the heat source and the CPCM, to cool down the temperature of the heat source more effectively.

In order to obtain the amount of the heat stored in the substrate during this experiment, the heat diffusion was also calculated. Similarly, we got that the total heat dissipation Q_{con} by natural convection was 96836.37 J by Eqs. (1)–(4) and the heat input Q_{in} of the heat source was 18,000 J according to Eq. (5). The sensible heat absorbed by the heat source Q_{heat} and the walls of the substrate Q_{sub} was calculated by Eq. (8) as 10086.65 J and 15,541.34 J, respectively. Therefore, we can obtain the experimental heat storage of the CPCM based substrate 57,535.64 J, while the theoretical heat storage was 54,697.59 J, which accounted for 31.96% of the heat input. Comparing with the theoretical value and the experimental value of the heat storage, the experimental error was calculated by Eq. (9) to be 5.20%.

HEAT TRANSFER ENHANCEMENT

From the preceding results, we can see that a great deal of heat was well stored in the substrate. However, because of the poor thermal conductivity of the CPCM, the heat generated by the heat source could not go into the CPCM quickly enough and the heat source temperature was much higher than the melting temperature of the paraffin. In order to improve the internal heat transfer properties of the substrate for the further step, we added five aluminum pillar fins symmetrically on the bottom side of the substrate. The configuration and location of the pillar fins are displayed in Figure 8 and the height of the pillar fins was 50 mm. The experimental setup was the same as was shown in Figure 4 and the results are shown in Figures 9 and 10.

Because of high thermal conductivity of the aluminum pillar fins, when the pillar fins were added into the substrate, several heat flux passageways with relativity low thermal resistance were formed. Consequently, the heat went to the passageways quickly and the pillar fins were well heated. The temperature of the pillar fins was close to that of the bottom of the substrate. Owing to the pillar fins, the heating area of the CPCM was largely extended. As a result, the heat storage speed increased and the temperature rising rate of the heat source decreased. On the other hand, because more of the heat generated by the heat source was absorbed and stored into the CPCM in the unit time, the heat dissipation load of substrate through natural conduction

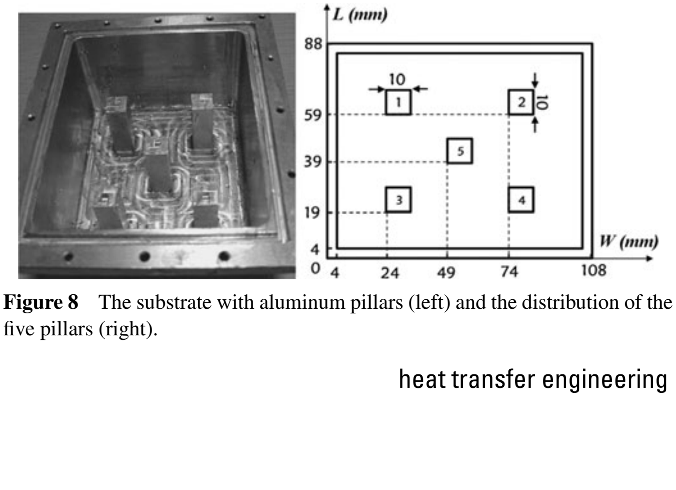

Figure 8 The substrate with aluminum pillars (left) and the distribution of the five pillars (right).

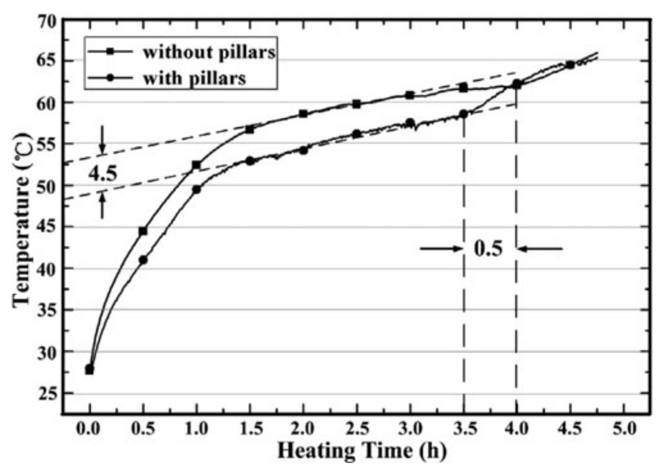

Figure 10 Comparison of the substrate temperatures.

was diminished. The temperature of the substrate also decreased during the latent heat storage period as a consequence.

In this portion, the heat storage performance was compared between the substrate with/without pillar fins and the temperature curves of the heat source and the substrate wall were displayed in Figure 9 and Figure 10 separately. It showed that with the aluminum pillar fins, the latent heat storage stage began earlier, and the heat source temperature and the substrate-wall temperature decreased by about 3.5°C and 4.5°C, respectively. For the substrate with pillar fins, there was a sharp temperature increase after heating 3.5 hours, while the increase postponed 30 minutes for the substrate without pillar fins. We can conclude that with the aluminum pillar fins, the heat transfer was enhanced and a faster latent heat storage rate was acquired.

CONCLUSIONS

The paraffin/expanded graphite composite phase-change material (CPCM) was prepared and the phase transition properties of the paraffin and the CPCM were obtained by the DSC test and the thermal conductivity test. It is concluded that the paraffin has good compatibility with the expanded graphite and keeps stable thermal properties when absorbed by the expanded graphite. During the experimental investigation of the CPCM-based substrate for the thermal management of electronic devices, it proved that the substrate could store the heat and the temperature of the substrate and heat source had relatively small increase when the PCM melted. Furthermore, the experimental and theoretical calculation of the heat stored in the CPCM-based substrate was carried out and the results showed that about 32% of the heat input was stored in the substrate. To enhance heat conduction in CPCM, the aluminum pillar fins were added into the substrate. With the pillar fins, the substrate had better heat storage performance and the temperature of the heat source and the substrate-wall decreased efficiently.

FUNDING

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NOMENCLATURE

A	heat transfer area, m^2
c	characteristic constants, dimensionless
C_p	specific thermal, J kg^{-1} K^{-1}
CPCM	composite phase-change material
DSC	differential scanning calorimeter
g	acceleration gravity, m s^{-2}
Gr	Grashof number, dimensionless
H	latent heat of phase change material, kJ kg^{-1}
h	heat-transfer coefficient, W m^{-2} K^{-1}
L	length of the surfaces, m
l	characteristic length, m
LED	light-emitting diode
m	mass of the materials, kg
n	characteristic constants, dimensionless
Nu	local Nusselt number, dimensionless
P	heat power of the heat source, W
PCM	phase-change material
Pr	Prandtl number, dimensionless
Q	heat, J
T	temperatures of the materials, K
t	heating time, s
t_w	characteristic temperature, K
T_∞	temperatures of the ambient, K
ΔT	temperature difference, K
W	width of the substrate, m

Greek Symbols

β	volume coefficient of expansion, K^{-1}
η	experimental error, dimensionless
θ_w	temperature difference, K^{-1}
λ	thermal conductivity of the PCM, W m^{-1} K^{-1}
ν	kinematic viscosity, $m^2 \cdot s^{-1}$
Φ	heat flow, W

Subscripts

con	natural convection
gra	graphite
heat	heat source
in	input heat
m	melting
pra	paraffin
store	storage heat
sub	substrate

Superscripts

exper	experimental
gra	graphite
pra	paraffin
theory	theoretical

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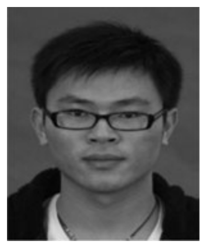

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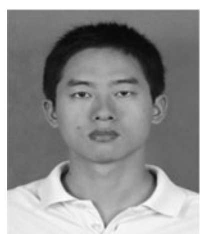

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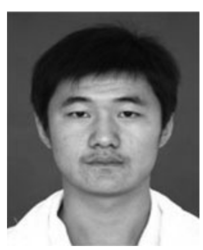

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