Charging method of micro heat pipe for high-power light-emitting diode

Congming Li, Yi Luo, Chuanpeng Zhou, Qing Shan, Xiaodong Wang

Key Laboratory for Micro/Nano Technology and Systems of Liaoning Province, Dalian University of Technology, Dalian 116024, People's Republic of China
E-mail: luoy@dlut.edu.cn

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Since high precision of working fluid charging is key to the evaluation of thermal performance, a novel perfusion method of a micro heat pipe (MHP) is presented. The MHP has a length of 26 mm, width of 20 mm and a thickness of ∼2.2 mm. The predetermined quantity of perfusion is 25 or 35 µl. Small volume and large capillary force render conventional vacuum perfusion methods quite impractical. To realise microscale and high precision of perfusion, the method of combining vacuum perfusion using a peristaltic pump and weight comparison before and after working fluid charging was used. The charging deviation of the method was <2 µl. After perfusion and sealing, the thermal performance testing of a MHP, which is engineered in light-emitting diode (LED) heat dissipation, was conducted and the input power varied from 1 to 7 W. The results show that high-power LEDs can reach the status of heat balance and can work steadily, and the maximum deviations of actual and simulated temperatures are 4.5 and 5.1°C, respectively, and the relative errors are 6.1 and 7.3%. Therefore, this perfusion method can be used for the working fluid perfusion of the MHP and makes it feasible for use in packaging manufacture of heat pipes.

1. Introduction: It is the rapid increase of thermal design power and the miniaturisation of electronic devices that restrict the development of high-power devices because of high thermal flux. In recent years, the luminous efficiency of high-power light-emitting diodes (LEDs) has reached up to more than 100 lm/W, which makes LEDs the main light source [1–3]. However, there is still about 70% of the electric power transformed into heat which causes an increase in junction temperature [4]. If the junction temperature of the LED is too high, the effective compound of the carrier is likely to decrease. It results in the luminous efficiency becoming small and even the LED chip being damaged [5–7]. Therefore, effective heat dissipation is important for high-power LEDs. However, the conventional single-phase radiator has reached its heat transport limitation. The heat pipe, with the advantages of high thermal conductivity [8, 9], and excellent isothermal and heat dissipation rate, is attracting increased attention in the electronic cooling domain. The micro heat pipe (MHP), as the main connection part of an LED chip and fin, can deliver the heat from the LED chip to the fin in time, and the chip temperature will not be too high.

Working fluid charging is an important process of MHP encapsulation [10], and the vacuum degree, quantity of working fluid and the sealing technique have great effects on the heat transfer performance of heat pipes. Some research groups have proposed methods to improve the packaging quality of the MHP. The method of vibration is used to charge the working fluid into the MHP, and then the MHP is sealed after the redundant fluid is eliminated from the MHP by heating [11]. Oshman *et al.* [12] first pumped the MHP to a predetermined degree of vacuum, then filled the pipeline with working fluid and opened the charging valve to charge the working fluid until the MHP was sealed. An induction heating-based non-invasive hermetic sealing approach for permanently sealing the degassed and charged micro loop heat pipe (MLHP) devices was proposed in [13]. However, there are still two main problems left for the MHP encapsulation technique [1, 9, 14–16]. One is that the internal capacity of a heat pipe charged by the conventional method is bigger to about several millilitres or tens of millilitres; at present, the filling volume is reduced to tens of microlitres. Conventional filling methods are no longer suitable for MHPs. Besides, there exists a greater pressure differential which is bad for accurate working fluid charging, which is the other problem. Therefore, all of these factors should be considered when charging the working fluid into the MHP accurately.

Some traditional heat pipes, for example, oscillating heat pipes (OHPs) and LHPs, have been researched for the heat transfer of LEDs. The investigation of the heat transfer characteristics of an aluminium plate OHP was carried out, and an LED heat sink design with a plate OHP was developed. From comparison of temperature records between conventional tubular and plate OHPs, the results proved that aluminium plate OHPs were more beneficial for electronic cooling [17]. Aluminium plate with high thermal conductivity is applied as a radiated circuit plate for high-power LEDs [18]. In [18], theoretical analysis and experimental research were conducted using a 144 W illuminator. To improve the thermal characteristics of the high-power LED package by using an LHP, experimental thermal analysis was conducted. It is demonstrated that the LHP is a good solution for controlling the junction temperature of high-power LED systems of more than 50 W [19].

There have been a lot of experimental studies on the thermal performance, and most heat pipes belong to the sintered and OHPs types. There are only few researches on silicon (Si) MHPs, without a porous wick structure, which are based on the MEMS technique. The heat flux mentioned above can reach up to 1.2×10^5 W/m^2 [17–19], but the heat flux of LED chips on Si in this Letter is more than 2.1×10^6 W/m^2. It also makes heat dissipation more difficult. In this Letter, Si MHPs with copper grooves based on the MEMS technique were used. The temperature distribution of MHPs with nine LED chips was simulated using ANASYS software. Then it was compared with experimental results. What is more, a novel perfusion method is proposed to solve the two problems mentioned above. According to the working principle of the peristaltic pump, the Si tube across the pump was clamped during the whole process. It can reduce the influence of differential pressure between in and out of the charging circuit, and then make the charging more accurate. Filling ratio, vacuum degree and inclination angle have a great effect on the thermal character of MHPs. For this reason, it is necessary to implement more advanced experimental investigations on MEMS MHPs.

2. Method and experiments

2.1. Fabrication of MHP substrate: Three kinds of MHP substrates with different groove structures were fabricated, and the detailed dimensions are shown in Table 1, and the fabrication procedure was previously described in [20]. The overall dimensions of the

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Table 1 Design dimensions of MHP substrates

Number	Width of channels, µm	Space between channels, µm	Depth of channels, µm
one	100	100	~65
two	100	50	~65
three	150	50	~65

substrate was 20 mm (width) × 26 mm (length) × 1 mm (thickness), and the width and length of the working area were 13.5 and 20 mm, respectively, as shown in Fig. 1*b*. Copper microgrooves were fabricated by the electroforming process on the *n*-type Si (100) wafer. The depth of channels was about 65 µm.

2.2. Assembly: As shown in Fig. 2, on one hand, the substrates in the wings and the copper cover plate were enveloped by using sealant; on the other hand, the substrates with LED chips on the opposite side can be spliced together with a copper heat sink. Fig. 1*a* shows the distribution of nine LED chips on the Si substrate. The MHP without the LED is used in the thermal performance test, whereas the MHP with the LED is for application study in the LED lighting domain.

2.3. Internal volume measurement of MHP: The internal volume of the MHP was measured to ascertain the encapsulation quantity. Before the encapsulation of MHPs, an inductance micrometer (Millitron1240, Mahr GmbH Göttingen, Germany) was used to

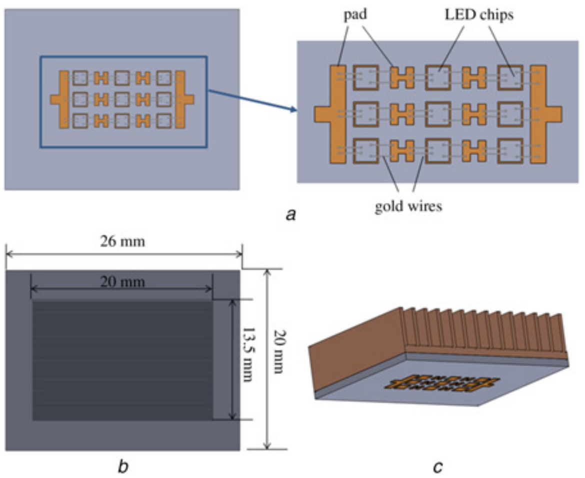

Figure 1 *LED module with MHP and copper fin*
a Front panel of Si substrate
b Rear panel of Si substrate
c LED module

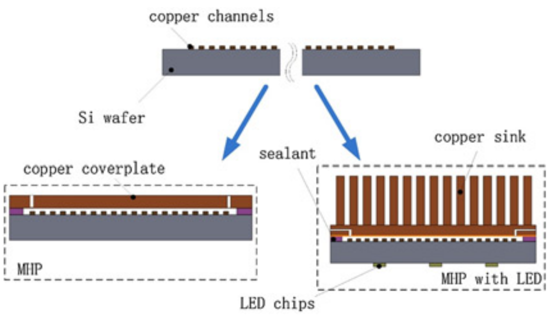

Figure 2 *Two kinds of encapsulation of MHPs*

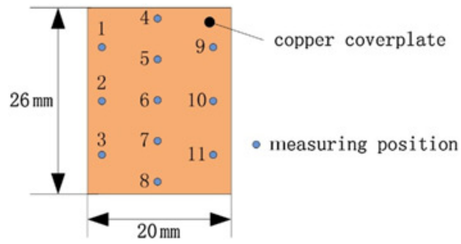

Figure 3 *Schematic diagram of measuring positions*

measure the thickness of the copper cover plate, and 11 measuring positions are shown in Fig. 3. The thickness of the copper cover plate is ~1.2 mm, whereas the Si wafer is 1 mm with a tiny uncertainty which can be ignored. After the encapsulation of the MHP substrate and the copper cover plate with sealant, the same measuring positions were measured again using the inductance micrometer. The thickness of these positions before and after encapsulation were marked as P1 – P11 and P′1 – P′11, respectively, and then the mean thicknesses of the sealant could be obtained. Finally, according to the dimensions and size of the MHP substrate in Table 1, the internal capacity of the MHPs was confirmed.

2.4. Working fluid charging method: It is hard for MHPs to measure the actual internal vacuum degree due to the smaller internal volume and the smaller radius of the pipeline. To accurately obtain the reading of a predetermined vacuum degree, this Letter fixed the MHP between the vacuum pump and the vacuum gauge so that the real vacuum degree in the MHP must be little higher than the vacuum meter display. Besides, a polypropylene (PP) pipe was used in this pipeline, because of its thermoplasticity and small inner diameter. The peristaltic pump (BT100-1F, Konap Peristaltic Pump Company, China) with a precision of 0.006 ml/min can implement microscale charging, and it can solve the problem of the pressure differential because of its working principle. Hence, MHPs can be sealed quickly, efficiently and accurately.

Fig. 4 shows the working principle of a peristaltic pump. Hence, we know that the roller can divide the Si tube into two parts, and this makes the pipeline hermetic. The fluid flow rate is proportional to the rotational speed of an electrical machine, so the charging quantity of the working fluid is controlled by the rotational speed and rotational time of the electrical machine.

The two-step method of charging, peristaltic pump charging and differential weighing, was used in this Letter to ensure charging accuracy. First, the peristaltic pump can charge the working fluid with microlitre grade into the MHP, but there is a slight deviation; then, the deviation can be calculated by differential weighing. Finally, we can obtain an accurate perfusion result. The following text is the specific implementation process.

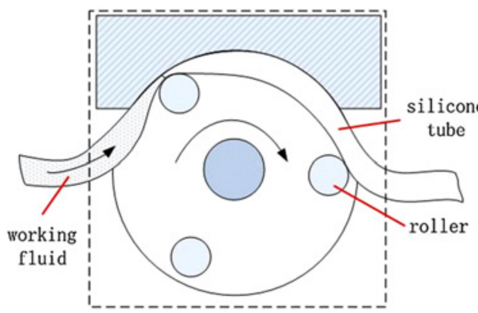

Figure 4 *Working principle diagram of peristaltic pump*

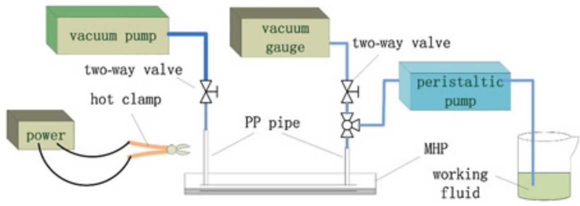

Figure 5 *Working fluid charging system of MHP*

Before charging, we used a high-precision balance (ME204, Mettler-Toledo, China) to weigh the MHP and record its weight as G1.

The process of the peristaltic pump charging method can be described as follows. (i) Connect the circuit as shown in Fig. 5, and open the two-way valve 1 and the two-way valve 2. (ii) Then open the vacuum pump to pump air out from the pipeline. (iii) When the pressure of the vacuum gauge display is smaller than 5 Pa, use a hot clamp to seal the PP pipe on the left side of the MHP. (iv) Close two-way valves 1 and 2, and transfer the working fluid into the pipeline under the transmission mode of the peristaltic pump. (v) Until the working fluid arrives at the right entrance of the MHP, stop the peristaltic pump, switch transmission mode to allocation mode and then start the pump again for predetermined charging. (vi) When the peristaltic pump stops, the PP pipe on the right side of the MHP is sealed by using a hot clamp. The charging and sealing process of the MHP is complete.

A high-precision balance was used to weigh the severed PP pipes and the MHP after sealing, and the weight was recorded as G2. Hence, the quantity of the working fluid in the MHP can be expressed as G2–G1.

2.5. Simulation: Owing to the complexity of working fluid phase change in MHPs, it is very difficult to simulate the temperature distribution accurately. Only the MHP with a copper heat sink without working fluid was simulated using ANSYS to show the temperature distribution, where heat was mainly transferred by thermal conduction.

By comparing the results of the simulation and experimental measurements, we can obtain the temperature evaluation error. Then the temperature distribution of MHPs with working fluid was provided by means of experimental measurement.

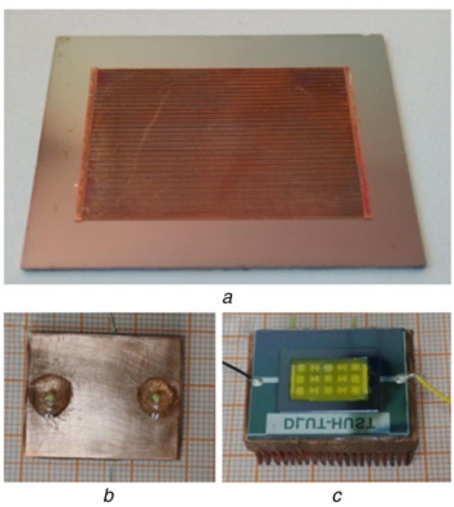

Figure 6 *MHP substrate and MHPs after encapsulation*
a MHP substrate with copper grooves
b MHP encapsulated with copper cover plate
c MHP encapsulated with copper heat sink

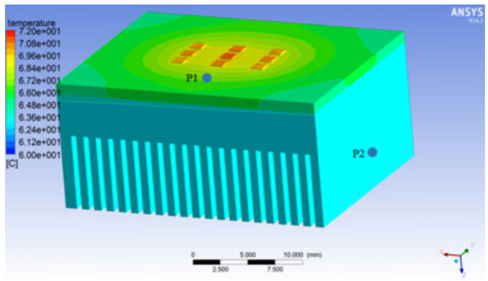

Figure 7 *Simulation of MHP-S without working fluid*

In the ANSYS simulation, the real input power was smaller than the electric power to the LED chips, as there is about 25% of the electric power for LED chips transformed into light. The contact thermal resistance between the LED chips and the Si substrate was ignored, while the contact thermal resistance of the Si substrate and the copper heat sink was set to 3.5×10^{-4} K m^2/W. As the experiment was conducted in a clean room with stable heat transfer, the coefficient of heat transfer was set as 8 W/m^2 K.

2.6. Testing: Both MHPs in Figs. 6*b* and *c* were tested, and they were marked as MHP-C (MHP with coverplate) and MHP-S (MHP with sink), respectively. The input power of MHP-C was supplied by ohmic heating rods, and its value could be obtain by a power analyser (PA1000, Tektronix, USA). Nevertheless, the input heat of the LED module was provided by LED chips, which cannot be detected directly. The real input power transferred to the heat pipe was equal to the difference of the electric power and the luminous power, the electric and luminous power being measured by a multimeter (2400, Keithley, USA) and an integrating sphere, respectively.

The experiments of MHP-C were carried out in the vacuum environment with forced water cooling, whereas MHP-S was tested under normal ambient condition without forced cooling. With good cooling condition, the input power of MHP-C varied from 2.7 to 7.4 W, whereas the input power of MHP-L only ranged from 0.9 to 3.9 W. For MHP-C, the temperatures of the evaporation section, the adiabatic section and the condensation section were measured; for MHP-S, only the temperatures of the heat sink and near LED chips were measured. The experimental results are graphed in Fig. 11.

3. Results and discussion: Fig. 7 shows the simulation result of MHP-S after being calculated for 1000 s, and the heat transfer has reached the stable state when the real input power is 2.25 W (corresponding to an electric power of 3 W for LED chips). The simulated temperature variations of P1 and P2 in Fig. 7 are shown in Fig. 8. Then the temperatures of the same two positions

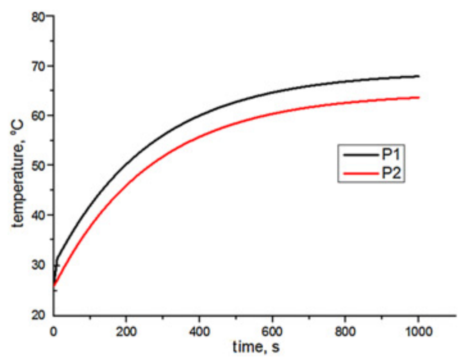

Figure 8 *Simulated temperature distribution variation of MHP-S without working fluid*

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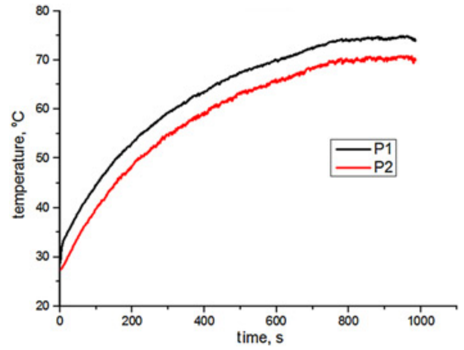

Figure 9 *Actual measured temperature variation of MHP-S without working fluid*

were measured when the test experiment of the MHP-S was performed in a clean room. The temperature variations are plotted in Fig. 8. From the simulations, after reaching the steady state, we know that there is ∼4°C of temperature gradient on the Si substrate; however, the total temperature difference of the copper heat sink is no more than 0.1°C

From Figs. 9 and 10, we can obtain the results that the maximum deviations of actual and simulated temperatures at P1 and P2 are 4.5 and 5.1°C, respectively, and the relative errors are 6.1 and 7.3%. Fig. 8 shows a stable tendency at about 800 s. Although there are a few differences between the simulated and actual results, the variation trend is very similar, and the amplitude of temperature variation is in a certain tolerance range. The reasons for these differences may be the fluctuations of the coefficient of heat transfer and the contact thermal resistance as the temperature of the LED chips increases.

The simulations under different input powers showed similar results to those above. Then to obtain the temperature distribution variation of MHPs with the working fluid, the experiment comparisons of MHPs with and without the working fluid were performed.

For different encapsulated MHPs, the entire internal capacity of the MHP varied from 50 to 70 µl. In this Letter, assuming that the optimum filling ratio is 50%, both MHP-C and MHP-S were charged five times, while the charging quantity of the working fluid was set to 25 and 35 µl, respectively.

Fig. 10 shows the real charging quantity of MHPs after charging five times. The results show that the maximum charging errors of MHP-C and MHP-S were 1.4 and 1.8 µl, respectively. At the beginning of the charging process, there was a bigger differential pressure between in and out of the pipeline. Once the working fluid flowed into the pipeline, the evaporation phenomenon appeared under the low pressure and then the pressure in the pipeline decreased sharply. Therefore, there was only a slight shock during this process. However, the internal volume was merely about dozens of

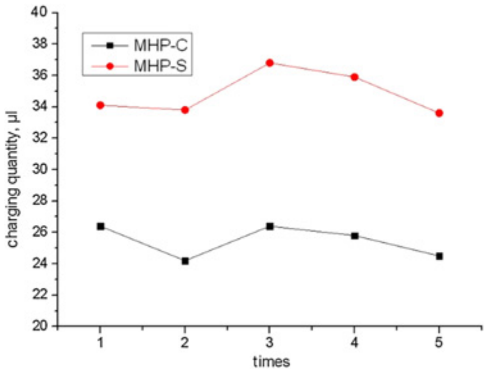

Figure 10 *Real charging quantity of MHPs charged five times*

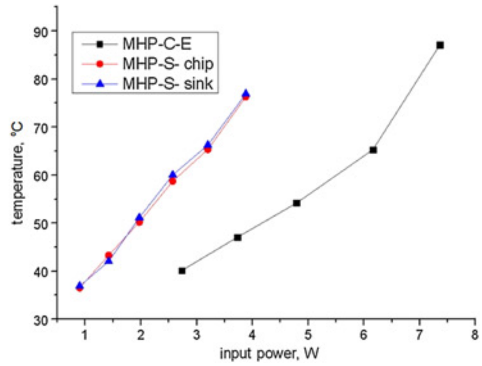

Figure 11 *Equilibrium temperatures of MHP-C and MHP-S under different input power (MHP-C-E, MHP-S-sink, MHP-S-chip represent the temperature of evaporation, heat sink and near LED chips)*

microlitres, so the saturated vapour pressure could reach equilibrium in a short time. Owing to this shock, several liquid slugs and air plugs were formed in the transmission tube. With the working fluid flowing in the tube, part of the plugs emerged or expanded; so to some extent, the air plugs made the quantity of charging fluctuant, this being the reason why charging errors appeared.

In Fig. 11, with the increase of input power, the evaporation section temperature keeps rising. When the power is greater than 6.5 W, the rate of temperature rise reaches the highest. Hence, it can be concluded that the heat transport limitation of MHP-C is within 6.5 W.

To evaluate the thermal performance of the MHP applied in LED heat dissipation, the temperatures of the heat sink side and near LED chips were measured. Relative to the forced cooling of MHP-C, the heat sink of MHP-S cannot effectively exchange heat with the ambient time when the input power is beyond a certain value. Hence, the heat-transfer capability of the MHP-S is lower. Fig. 10 shows the temperature changes of the heat sink and the near LED chips of MHP-S when the input power varies from 0.9 to 3.9 W.

Comparing Figs. 9–11, when the input power equals 3 W, the equilibrium temperature of the MHPs with the working fluid is about 10°C lower than the MHPs without the working fluid at the position of the near LED chips. It can also be seen in Fig. 11 that the temperature of the heat sink is almost equal to that of the near LED chips. That is to say, the LED device showed great isothermality, and the heat produced by LED chips could be delivered to the heat sink effectively by means of the latent heat of the phase change. However, the heat flux in the heat sink still remained higher, and the convective heat transfer between the heat sink and the ambient was limited so that the temperature of the LED chips will be greater than 90°C when the input power increases to more than 5 W.

4. Conclusion: Aiming to charge working fluid into the MHP accurately, a novel method using a peristaltic pump for charging has been developed and implemented. A PP pipe with good thermoplasticity was used to seal the charging hole. Specific to a perfusion quantity of only dozens of microlitres, the perfusion error of the method proposed in this Letter is <2 µl. Owing to the vapourisation of liquid during perfusion and the function of microforces, it is inevitable that the real charging quantity of the working fluid fluctuates.

After filling and sealing, thermal performance experiments of both MHP-C and MHP-S were conducted. With forced water cooling, the input power of MHP-C varied from 2.7 to 7.4 W, and MHP-C showed better heat transfer performance. The MHP embedded into the LED device can transfer heat effectively and makes the device isothermal. Hence, the perfusion method in this Letter could be used to charge MHPs, and it may promote the development of the application of MHPs in LED devices.

There still remains the necessity for more research on the transient simulation about phase change and the effects of filling ratio, vacuum degree and angle of incline on thermal performance. Further studies will focus on these elements and on the advanced promotion of heat transfer performance of MHPs.

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