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Experimental study on high-power LEDs integrated with micro heat pipe*

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Micro heat pipe (MHP) is applied to implement the efficient heat transfer of light emitting diode (LED) device. The fabrication of MHP is based on micro-electro-mechanical-system (MEMS) technique, 15 micro grooves were etched on one side of silicon (Si) substrate, which was then packaged with aluminum heat sink to form an MHP. On the other side of Si substrate, three LED chips were fixed by die bonding. Then experiments were performed to study the thermal performance of this LED device. The results show that the LED device with higher filling ratio is better when the input power is 1.0 W; with the increase of input power, the optimum filling ratio changes from 30% to 48%, and the time reaching stable state is reduced; when the input power is equal to 2.5 W, only the LED device with filling ratio of 48% can work normally. So integrating MHP into high-power LED device can implement the effective control of junction temperature.

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It is known that only 20—30% of power input for high-power light emitting diode (LED) is transformed into light, while the other dissipates in the forms of heat[1,2]. In recent years, with the power increases and the size of LED device decreases, the heat flux of heat source rises dramatically and causes the junction temperature higher, which results in the degradation of performance and even the damage of LED device[3-5]. According to relevant researches, the lifetime could be prolonged by two times when the temperature decreased by 10 °C[6]. Eventually, the key issue is how to solve the problem of heat transfer.

Heat pipe or vapor chamber as a passive heat transfer device has been widely used for thermal control of electronic and photonic devices[7-9]. However, due to the development trend in device power consumption and thickness, traditional heat spreading materials already cannot meet the needs. Especially, micro heat pipe (MHP) has been proposed to spread heat away from local hot spots. Compared with traditional heat pipe, micro channels instead of capillary wicks in MHP have been developed, and the characteristic dimension of MHP maintains at micron level.

Some combined-type device has been studied for high-power LED heat dissipation. Hao et al[10] combined aluminum heat sink with a novel flat heat pipe to solve the problem of high heat flux dissipation, and the stimulation results were obvious. Lu et al[11] developed a loop heat pipe (LHP) applied to the heat dissipation for LED, and experiments were performed to study the effects of heat load, inclination angle and heating method on the start-up time, temperature uniformity and thermal resistance of heat pipe. Sheu et al[12] and Kim et al[13] researched thermo-siphon heat pipe (THP), and found that the cooling effect of THP for LED was much better than that of copper-rod heat sink.

However, the heat dissipation objects of this paper are three LED chips of 3 W, and the heat flux can reach up to 78 W/cm^2 at local hot spot. To solve the problem of heat dissipation of high-power LED device, in this paper, MHP is applied to LED device to implement the efficient heat transfer by means of working fluid phase change and eventually to reduce the temperature of LED device. In order to evaluate the thermal performance of the proposed LED device with integrated MHP, experiments were carried out to study the start-up time and the optimum filling ratio at different input powers.

Dry etching was used to fabricate silicon (Si) microgrooves on the n-type Si (100) wafer. The flow diagram of fabrication process is shown in Fig.1. 15 micro

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grooves were etched on one side of Si substrate, both of the width and the separation distance are 100 μm, and the depth is 3 μm. However, the length, the width and the depth of groove area are 17 mm, 3 mm and 0.072 mm, respectively. Fig.2 shows the dimension details of the Si substrate.

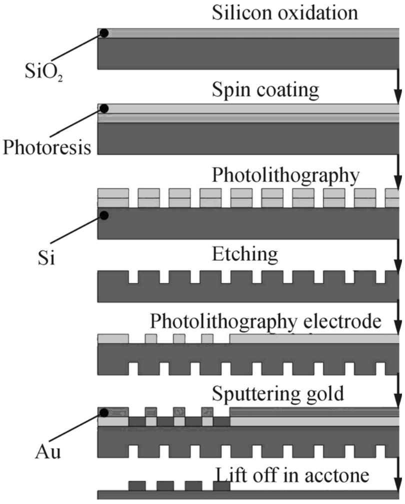
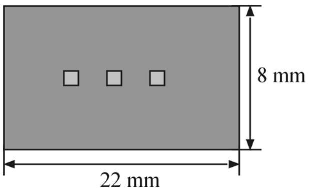
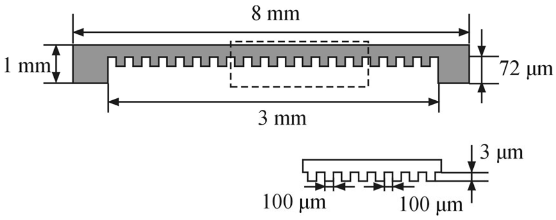


Fig.1 Flow diagram of Si substrate fabrication



(a) Top view with three LED chips



(b) Cross sectional view

Fig.2 Dimension figures of Si substrate

The photo of Si substrate with micro grooves is shown in Fig.3. The LED device presented in this paper consists of three LED chips, an MHP and an aluminum heat sink. The schematic diagram of LED device is shown in Fig.4. According to the MHP substrate mentioned above, it can be bonded with aluminum heat sink together using sealant to form an MHP.

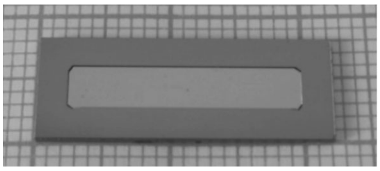


Fig.3 The photograph of Si substrate with micro grooves

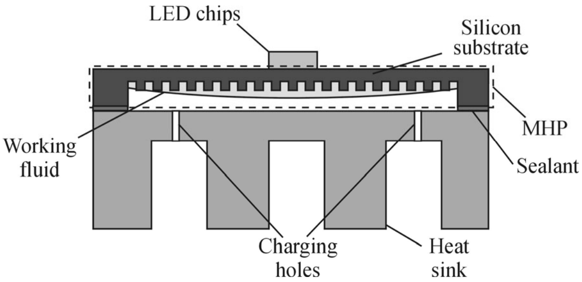


Fig.4 The schematic diagram of LED device

There exist three electrodes on the other side of MHP substrate for die bonding of LED chips, and the relevant parameters of LED chip are listed in Tab.1. It is known that MHP should have a certain amount of working fluid inside, so two charging holes across the heat sink are connected to the inner chamber of MHP. The detailed charging and sealing method has been described in Ref.[14]. Up to now, a whole LED device is obtained. The heat produced from LED chips firstly conducts to the upper side of MHP, which side is called as evaporation section, and then the heat is mainly transferred to heat sink in terms of latent heat by evaporation-condensation in MHP. Finally, the heat diffuses into air ambient under the effect of natural convection.

Tab.1 The relevant parameters of LED chip

Parameters	Values
Chip size (μm)	1 143×1 143×150
Au pad thickness (μm)	4.3±0.2
Forward voltage (V)	3.4
Forward current (mA)	350

In order to investigate the effect of filling ratio on start-up time and equilibrium time, several experiments were performed in clean room, where the room temperature is kept at 25 °C. The power input to LED device ranging from 1.0 W to 2.5 W was controlled by SourceMeter(Keithley2400, America), and the control procedure was developed based on proportional integral derivative (PID) algorithm using Labview software. Three thermocouples (Omega TT-K-36-SLE, America) were mounted on LED device to obtain the temperatures of the three positions, and details are demonstrated in Fig.5. Moreover, Fig.6 shows the schematic diagram of experimental setup.

Under the conditions of different filling ratios and different input powers, some experiments were performed to study the equilibrium temperature of LED devices and the start-up time of MHPs. Using the charging and sealing method mentioned in the authors' previous work[14] to charge the LED devices, four different filling ratios of 30%, 48%, 57% and 100% were obtained. And then these LED devices as well as a LED device without working fluid were employed in the performance experiments with the input power changing from 1.0 W to 2.5 W with an increase interval of 0.5 W.

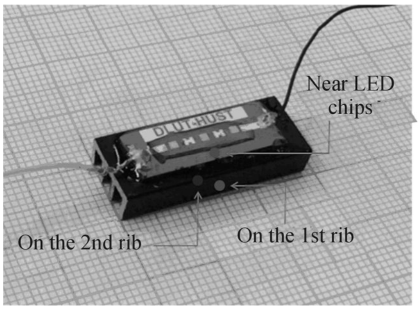


Fig.5 The photograph of LED device

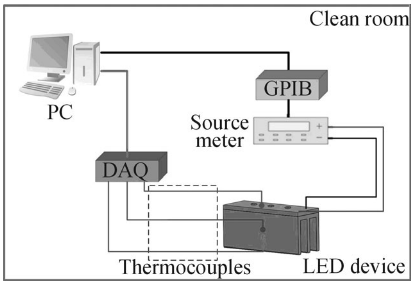


Fig.6 The schematic diagram of experimental setup.

Fig.7 shows the temperature variation curves of near LED chips when input power is 1.0 W. LED devices with higher filling ratios own lower equilibrium temperatures of below 50 °C, and the temperatures of the devices with filling ratio of less than 48% reach up to 60 °C. Meanwhile, it takes shorter time for LED devices with higher filing ratios to attain equilibrium compared with those with filing ratios. This is because that MHP may not start to work when input power is low, and the heat mainly transfers via the way of heat conduction. In this stage, the biggest restriction for MHPs to start up is viscous limit when heat load is small.

As shown in Fig.8 with input power of 1.5 W, the temperature differences among LED devices become a bit small, while the temperature of LED device with filling ratio of 100% keeps the highest. LED devices with filling ratios of 30% and 48% can attain stable state within 400 s, meanwhile, the temperatures of other three LED devices continue to increase. That is to say, MHPs in previous two LED devices can work well, and the LED device with filling ratio of 30% works better than that with filling ratios of 48%.

In Fig.9, the LED device with filling ratio of 30% shows the best performance among five LED devices when input power is increased to 2.0 W. Comparing with Figs.7 and 8, it can be found that the time reaching to stable state for LED device with 30% working fluid reduces from 350 s to 250 s with the increase of input power. For input power of 2.5 W, the performances only for LED devices charged with working fluid were conducted. As shown in Fig.10, only one device with filling ratio of 48% can maintain constant temperature and keep the temperature below 100 °C, while the temperatures of other devices are all beyond 100 °C and keep increasing. In this stage, boiling limit is proved to be the major factor affecting the thermal performance of MHPs.

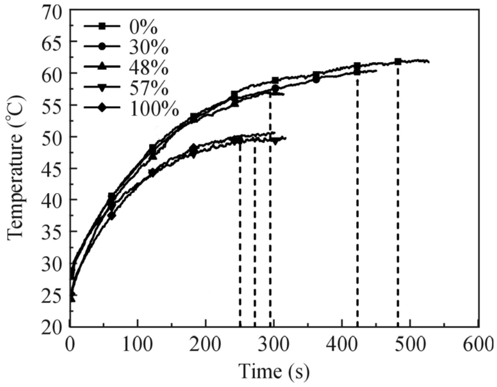


Fig.7 Temperature variation curves of near LED chips with different filling ratios when input power is 1.0 W

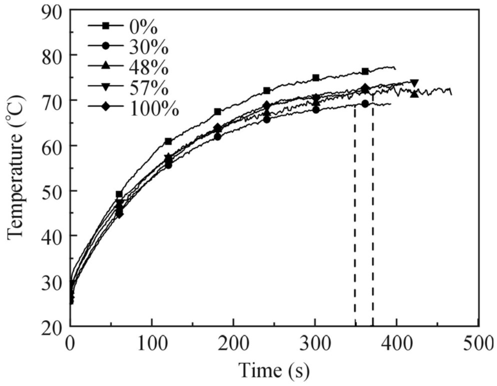


Fig.8 Temperature variation curves of near LED chips with different filling ratios when input power is 1.5 W

In this paper, experiments were conducted to study the thermal performance of LED devices based on working fluid charging and sealing method. The input power was varied from 1.0 W to 2.5 W with an interval of 0.5 W and five LED devices with different filling ratios were tested. The results show that the optimum filling ratios are 30% and 48% for input powers of 1.5 W and 2.5 W, respectively,

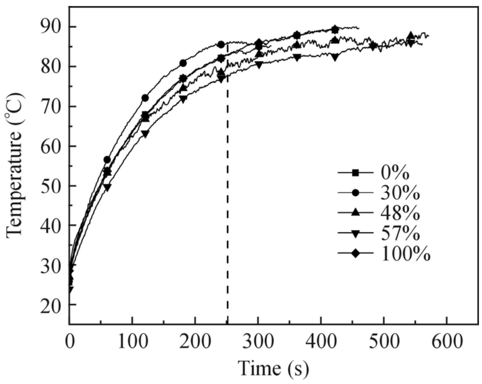


Fig.9 Temperature variation curves of near LED chips with different filling ratios when input power is 2.0 W

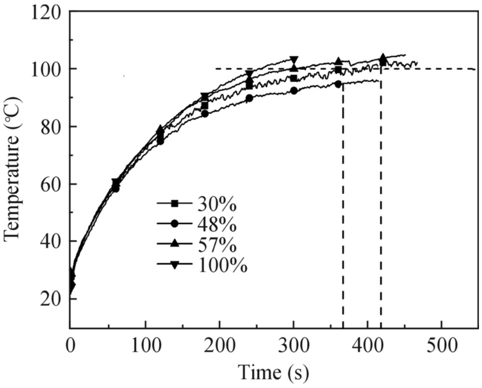


Fig.10 Temperature variation curves of near LED chips with different filling ratios when input power is 2.5 W

and the equilibrium time reaching to stable state for LED device with filling ratio of 30% reduces from 350 s to 250 s with the increase of input power. So it can be concluded that the suggested power to work for LED device charged with 30% working fluid is 2.0 W, and that for the one charged with 48% working fluid is 2.5 W.

Also, other factors, such as ambient temperature, flow characteristic of working fluid and micro groove structure, may have great effect on the heat transfer performance. So we will focus on these factors for further study.

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