Thermal behavior of silicon-copper micro vapor chamber for high power LEDs*

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Micro vapor chamber (MVC) for light emitting diodes (LEDs) can be designed and fabricated to enhance the heat dissipation efficiency and improve the reliability. In this paper, we used photoresist SU-8 and electroforming copper (Cu) to fabricate three kinds of wick structures, which are star, radiation and parallel ones, and the substrate is silicon with thickness of 0.5 mm. Electroforming Cu on silicon to make micro wick structure was a critical step, the ampere-hour factor was used, and accordingly the electroforming time was predicted. The composition of electroforming solution and parameters of electroforming were optimized too. After charging and packaging, thermal behavior tests were carried out to study the heat dissipation performance of MVCs. When the input power was 8 W, the parallel wick structure reached the equivalent temperature of 69.0 °C in 226 s, while the others were higher than that. The experimental results prove that the wick structures have significant influence on the heat transfer capability of MVCs.

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Vapor chamber (VC) is a solution to the poor heat dissipation capability of light emitting diodes (LEDs). Faghri et al[1] aimed to three kinds of Cu-water micro vapor chambers (MVCs) with different dimensions and structures, and the results demonstrate that the high-aspect-ratio channel heat pipe has better heat transfer performance. Peng[2] investigated the heat transfer performance of VCs with different cooling air-flow velocities, working fluid charge ratios and vacuum degrees. Naphon[3] conducted a series of experiments with different coolant types, flow directions of coolants and heat sink configurations. Recent years, many investigations about the incline angle[4], new micro wick structures[5] and new types of heat pipes[6] have been also proposed to enhance the performance of VCs. Micro electroforming can be used to fabricate regular wick structure in MVC. Guan[7] analyzed the metallographic phases of electroforming deposits with different current densities. Nan[8] studied the composition of electroforming solution and summarized the optimal proportion of it. However, the microscopic structure nonuniformity is a problem of this technique. Therefore, how to improve the flatness of the microstructure is a main research orientation recently[9,10].

This paper is to fabricate micro copper (Cu) groove wick structures by electroforming to enhance the heat transfer capability of VC on account of the high heat conductivity coefficient of Cu. Moreover, the microstructure of electroforming was well organized and controllable, hence the capillary structure can be designed to be diverse. Three typical structures were designed and fabricated to investigate their influence on heat transfer capability.

Three kinds of micro groove wick structures, namely star, radiation and parallel ones, were designed. The dimension of the Si substrate is 26 mm×20 mm×0.5 mm and the work area, also the electroforming area, is 20 mm×15 mm. The target electroforming height is 120 μm.

The Si wafer was cleaned using a standard RCA cleaning method, then oxidated for 12.5 h to get a 1 μm thick SiO_2 layer, and then 50 nm thick Ti and 200 nm thick Cu were sputtered on the wafer as a conducting electrode. As a transition layer, BN308 can intensify the bonding strength of photoresist and the seed layer, so BN308 photoresist was needed before SU-8. To guarantee the insulation of each channel, the SU-8 height was selected as 200 μm, 80 μm higher than the target elec-

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troforming height. The schematic procedure of preparing SU-8 electroforming mold is shown in Fig.2(a)—(h).

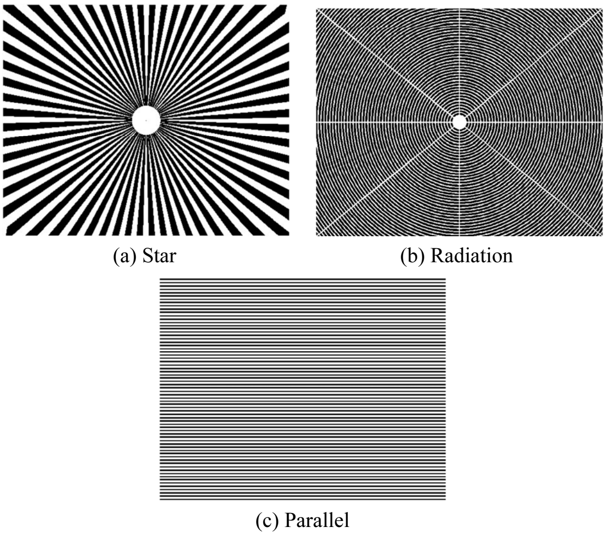

Fig.1 Design of three kinds of micro channels

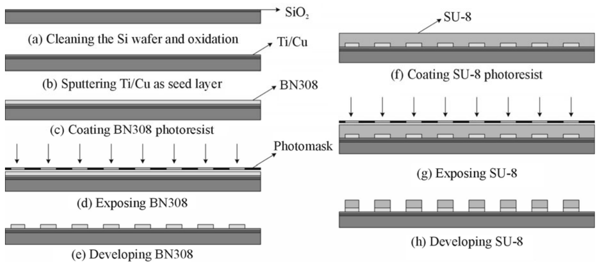

Fig.2 Procedure of fabricating the SU-8 electroforming mold

To accurately control the electroforming quantity, a parameter AH is used. When the cathode acquires 1 ampere-hour electron, the quantity of depositional Cu is 1AH. Theoretically, 1AH is equivalent to 1.185 1 g or 132.858 75 mm^3 Cu:

$$AH = \frac{H \times S}{1\ 000V} = \frac{H \times S}{132.858\ 75}, \tag{1}$$

where S is the efficient electroforming area of cathode, and H is the electroforming height.

Based on Guan's[7] study about the effect of current density, J=2 A/dm^2 is optimal for electroforming, and we can calculate the optimal current I as follows

$$I=JS. \tag{2}$$

The electroforming area is S=1 986.027 8 mm^2 in total, the target height is H=120 μm, so we can obtain the target AH of 1.794 and optimal I of 0.4 A. To get an orderly compactness, the current is successively set as three steps to reach 0.4 A. The target electroforming time is T=279 min.

Before electroforming, the electroforming solution needed to be compounded appropriately, which contains 70 g/L $CuSO_4$, 200 g/L concentrated sulfuric acid, 0.1 mL/L cupracid FP additive and 2 mL/L cupracid FP leveller. The volume of the electroforming machine (EP100-A, Info Bright Technologies) is 32 L, and baffles with 60 mm diameter were placed round the hole at intervals of 50 mm. After the electroforming, the wafer was cut into rectangles with the area of 26 mm×20 mm and the SU-8 photoresist was removed by fuming sulfuric acid. The finished substrates are shown in Fig.4.

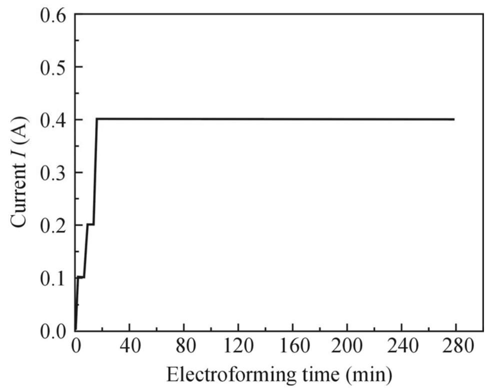

Fig.3 The current diagram of electroforming

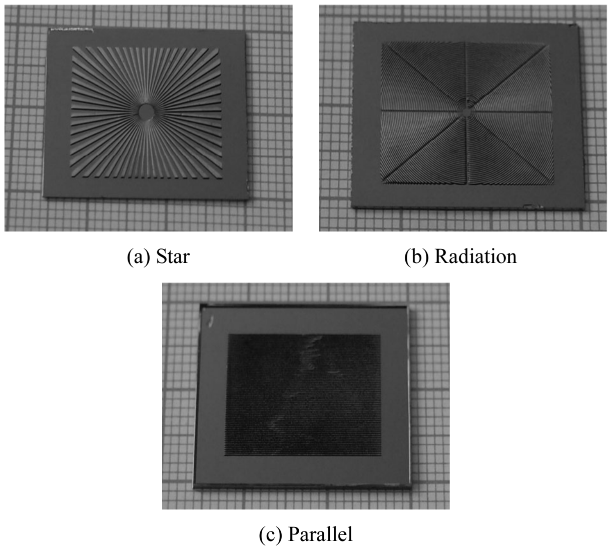

Fig.4 The electroformed silicon-based Cu grooved substrates

The Si substrate and Cu cover plate (26 mm×20 mm×2 mm), as shown in Fig.5, were packaged by sealant. The vapor chamber is between the two parts and the volume can be accurately calculated using the electronic balance (ME204, Mettler Toledo). The maximum measurement range is 200 g and the accuracy is 0.000 1 g. The volumes of the three MVCs are V_{star}=127.25 μL, $V_{radiation}$=93.26 μL, and $V_{parallel}$=103.13 μL, respectively. The coolant deionized water was injected into the chamber under precise control, the detailed charging process is shown in Ref.[11], and the final filling rate is 20%—30%.

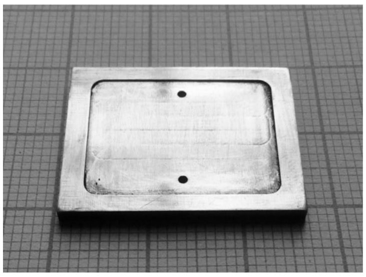

Fig.5 The Cu cover plate

To monitor the heat dissipation performance, a thermocouple (OMEGA TT-K-36, accuracy of ±1.05 °C)[12] was placed at evaporation section, just beside the LED chips. The MVC was cooled by circulating cooling water which is 20 °C in a vacuum chamber. The real-time temperatures were transmitted to the upper computer and compared by LabVIEW[13]. The input power ranges from 1 W to 8 W.

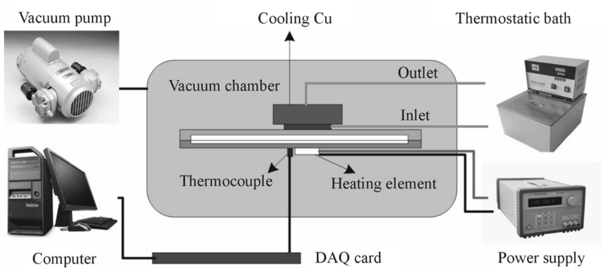

Fig.6 Schematic diagram of the thermal performance testing system

The equilibrium temperatures of three kinds of Cu wick structures are shown in Fig.7. In the same experimental situation, the parallel wick structure has the lowest equilibrium temperature, while the star one has the highest. The performance of the radiation structure is similar to that of the parallel structure. When the input power is less than 5 W, the radiation structure's performance is a little better, while the parallel performance is a little better when the input power is 5—8 W. These results indicate that the capillary force also plays an important role in MVC. Compare with star structure, the radiation and parallel structures have high capillary force, so they have higher heat transfer capability.

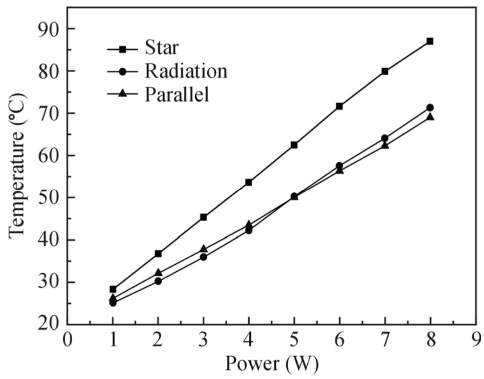

Fig.7 The equilibrium temperatures of evaporation section with different input powers

Fig.8 shows the equilibrium processes while the input power is 8 W. The equilibrium temperatures at evaporation section of star, radiation and parallel VCs are 86.9 °C, 71.3 °C and 69.0 °C, respectively. The temperature of star structure is higher than that of radiation and parallel structures during the whole process. The temperature of radiation structure is lower than that of parallel structure before 93 s but exceeds it after that. The times to achieve the equilibrium state for three structures are T_{star}=260 s, $T_{radiation}$=289 s and $T_{parallel}$=226 s, respectively. The parallel VC is more easy to reach equilibrium state. Although the radiation structure has similar heat dissipation effect to the parallel structure in the same input power, it has longer equilibrium time. The test was repeated three times, and the results show the same trend.

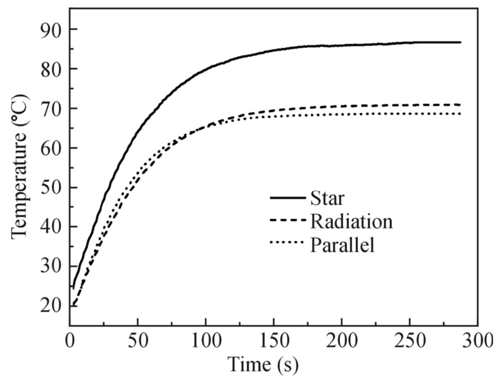

Fig.8 The equilibrium processes of evaporation section with input power of 8 W

According to Fig.7 and Fig.8, the thermal resistances from ceramic heating element to the cooling water of star, radiation and parallel structures are 4.69 K/W, 3.54 K/W and 3.13 K/W, respectively.

In this paper, a silicon-based Cu-grooved MVC for high power LEDs is designed and fabricated. The wick structures are star, radiation and parallel, which were fabricated by the electroforming technique. The fabricated MVC was charged by deionized water as working fluid with the charge rate between 20% and 30%. The thermal behaviors were tested in vacuum chamber with the cooling water at 20 °C. The experimental results show that the parallel wick structure is superior to the star and radiation structures in terms of equilibrium temperature and time, thus the wick structure plays a critical role in heat transfer performance of MVC. Moreover, the micro electroforming can enlarge the structural patterns and enhance the heat transfer capacity of Cu, which potentially provides more opportunities to improve the heat dissipation capacity.

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