Microelectronics Reliability 54 (2014) 1355–1362

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

A polymer based miniature loop heat pipe with silicon substrate and temperature sensors for high brightness light-emitting diodes

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ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 20 January 2014
Accepted 20 February 2014
Available online 26 March 2014

Keywords:
LED
Thermal management
Silicon substrate
Temperature sensors
Polymer loop heat pipe
Color properties

ABSTRACT

Solid State Lighting (SSL) systems, powered by light-emitting diodes (LEDs), are revolutionizing the lighting industry with energy saving and enhanced performance compared to traditional light sources. However, around 70%–80% of the electric power will still be transferred to heat. As the elevated temperature negatively affects the maximum luminous output, efficiency, light quality, reliability and the lifetime of the SSL systems, thermal management is a key design aspect for LED products. In this work, an innovative thermal management with a package, a silicon substrate with temperature sensors and a polymer based loop heat pipe (LHP) was designed, manufactured and assembled. It can supply a low and relatively stable temperature to maintain higher optical power, more luminous flux and less color shift. In a word, the novel design can provide LEDs with the efficient thermal management and temperature monitoring with reduced weight, easy fabrication, less energy consumption and better light quality.

1. Introduction

In comparison to the incandescent lamp, Solid State Lighting (SSL) system, powered by light-emitting diodes (LEDs), consumes about one-tenth of the power [1,2]. Nowadays, LEDs are enabling novel applications with energy savings and environmental benefits. However, still around 70%–80% of the input power will transfer to heat [3]. As the elevated LED temperature directly affects the maximum light output, efficiency, quality, reliability and the lifetime of the SSL systems, thermal management is a key design aspect for LED products in terms of cost and performance [4]. The drive to obtain more light output is increasing, and consequently more heat needs to be dissipated from the LEDs. Current materials and novel thermal solutions all require heat sinks which are indispensable to dissipate heat to the environment. However, the bottleneck is always the low convection efficiency from solid surface to air [5]. Thus, more area is needed for better convection. To achieve more surface area with a solid, generally larger volume is required, resulting in bulky and heavy heat sinks, leading to unattractive LED products with cumbersome metal bulk. Besides, most highly thermally conductive materials are opaque and the heat sinks then completely prevent light transmission through them.

Liquid cooling can enhance thermal management with simple structure, transparency and small weight [6] as it can replace the same volume of traditional metallic heat sinks. Furthermore, liquid can remove the heat rather than conduct it which performs as better "thermal conductivity" than solid [7,8]. Liquid cooling has already been successfully applied in many semiconductor microelectronic applications [9] and will be easily used in LEDs. With exception of leakage and reliability, the driving force is major obstacle for setting the liquid cooling in the limited volume of LED product. Generally, small volume of liquid can be mainly driven by: micro-pump and heat pipe. Several micro-pumps have been introduced by Gravesen et al. [10], but they all require extra electric energy which might deviate from the slogan of "high efficiency" of LEDs. Therefore, the heat pipe (HP) which is driven by the waste heat is more appealing. Especially, the loop heat pipe (LHP) possess all the main advantages of traditional HPs, but obtain special properties to transfer heat for distances up to several meters at any orientation in the gravity field [11,12]. Polymer can be one of the best materials to archive easy fabrication, light weight and transparency for thermal management of LEDs. Besides, the normal operation temperature ranges of thermo plastics are quite close to SSL systems. However, poor thermal conductivity limited the applications until the combinations of polymer and liquid cooling were first reported. In 2001, McDaniels and Peterson [13] presented analytical modeling and estimated the thermal conductivity of a flat, flexible, polymer HP with a grooved wicking structure to be

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http://dx.doi.org/10.1016/j.microrel.2014.02.032
0026-2714/

approximately 740 W/m K. A design of micro HP (MHP) channels with polypropylene consists of flexible rectangular or trapezoidal micro channels fabricated with methanol and ethanol as the working fluids was investigated [14]. Then, Oshman et al. [15] fabricated a HP on a flexible liquid crystal polymer substrate using micromachining techniques compatible with printed circuit board technologies. The device transfers up to 12 W of power with an effective thermal conductivity of up to 830 W/m K.

In addition, LEDs also offer controllability of their spectral, spatial distribution, color temperature, etc. To control such "smart" light sources, "smart" thermal management is required. It is necessary to monitor and control the temperature of LED chip because the light performance is sensitive to temperature variation. Temperature can introduce color shift and consequently undesirable light quality [3,16]. To achieve the controlled thermal management, integrated temperature sensors on silicon can be a better choice [17] compared to the more complicated junction temperature measurement [18,19].

In this work, a novel polymer based LHP with ethanol as working fluid was designed, fabricated and assembled in order to cool LEDs to lower temperature and obtain better light performance. The polymer material demonstrated light weight and transparency; and the LHP highly improved the thermal conductivity of polymer. The boiling point can also supply a relatively stable working temperature to improve the LED performance. Besides, The LED chip was directly attached on silicon substrate with thin thermal interface material. A group of sensors can provide the accurate temperature measurement. The semiconductor diodes and resistors were calibrated for temperature sensing at the ranges from 30 °C to 150 °C. The monitored temperature can be used to control the active cooling for LED products in further work.

2. Design, fabrication and assembly

2.1. Silicon layer above polymer based miniature loop heat pipe

The polymer based miniature LHP was designed and manufactured with acrylic polymer. And a commercial LED package was chosen to position above the two-phase region with a polymer cover. However, the dimension of the package is too small and the polymer has very poor thermal conductivity as heat spreader. So a heat spreader made from silicon is inserted between the package and the polymer layer, which is shown in Fig. 1. And the LED package has the junction, lens, copper layer, ceramic part and thermal pad. In order to estimate the performance of the silicon substrate, a group of simulations was carried out first.

The LED package was considered as the heat source, and two simulations were conducted: one with the package directly attached on the polymer layer and the other one with the silicon heat spreader sandwiched between the LED package and polymer layer. The boundary conditions were: (i) a constant temperature at the bottom of polymer where it contacted with the two-phase region, (ii) natural convection and radiation at the surfaces except the bottom of polymer layer. In order to achieve accurate thermal simulation, 3D modeling with natural convection and radiation were conducted by Computational Fluid Dynamics in Ansys Fluent using 25 °C as ambient temperature. The material properties were chosen empirically and validated by previous work [5,6,20]. As shown in Fig. 2(a), the package contained a high temperature hot spot whereas the polymer layer was hardly heated. So the polymer cannot conduct heat from the small volume of hot spot to the two-phase region efficiently. A 0.5 mm thick silicon substrate demonstrated much better performance as a heat spreader in Fig. 2(b). Besides, the simulated junction temperature was significantly reduced from 196 °C to 115 °C with ethanol keeping the bottom temperature constant at 80 °C.

In Fig. 3, a group of simulation about simulated junction temperature versus the heat spreader thickness was conducted to optimize the thickness of the polymer-silicon layer. Firstly, if only the polymer is used as the heat spreader without silicon substrate, the junction temperature was very high which can permanently damage the LED and acrylic polymer. With increasing polymer thickness, the thermal performance became worse and worse. Secondly, even a very thin, 0.1 mm, silicon substrate can dramatically reduce the junction temperature. Thirdly, a thicker silicon layer led to lower junction temperature, but no significant improvements were observed. Therefore, as a very important component for polymer based miniature LHP, silicon substrate is indispensable as heat spreader. Besides, the required thickness of polymer layer between silicon and the two-phase region is always recommended to be as thin as possible. In this work, a 0.5 mm thick silicon layer was chosen, which is the standard thickness for a 4 in. wafer, and a 0.3 mm thick layer of polymer was designed with considerations of mechanical strength and durability.

2.2. Temperature sensors on silicon substrate

As the spectral and spatial distribution as well as color temperature of LEDs is affected by temperature, temperature sensors are required to monitor and even to control active cooling. However, the junction temperature measurement required several time calibrations and is relatively complex. The temperature sensors can be other option to monitor the temperature just under the LEDs which differs only slightly from junction temperature [19]. These temperature sensors can be simply integrated on silicon substrate shown in Fig. 4(a). Several sensors were developed with conventional silicon processing. Two P–N junction diodes, one P type and one N type resistor were designed just under the LED chip. And the aluminum layer can supply electric connection and work as reflection. The diode sensor is a common temperature sensor used in electronic equipment due to the advantage that it can be included in a silicon integrated circuit at very low cost. Fig. 4(b) shows the P–N junction diode which is fabricated in silicon substrate by doping with As^{+} and B^{+} ions. From diode equation, a linear

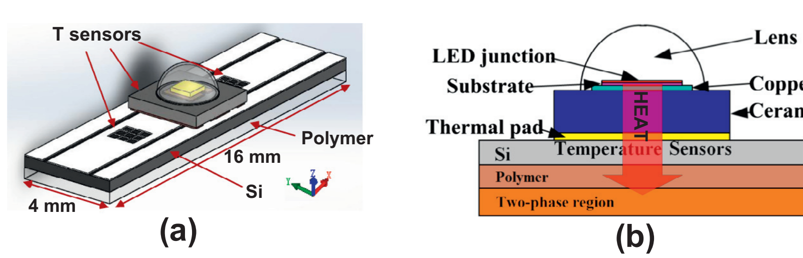

Fig. 1. (a) Illustration of silicon-polymer layer under a LED package; temperature sensors can be arranged under/beside the package on the silicon substrate; the polymer layer is above the two-phase region which is considered as constant temperature on the boiling point of working fluid during designing. (b) Schematic drawing of the cross section along the YZ plate; the heat generated from the LED junction and mostly through the package to the silicon substrate and removed by working fluid by its latent heat.