Energy 60 (2013) 195–203

Contents lists available at ScienceDirect

Energy

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

Cooling performance enhancement of LED (light emitting diode) packages with carbon nanogrease

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ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form
1 July 2013
Accepted 21 July 2013
Available online 7 September 2013

Keywords:
Carbon nanotube
Light emitting diode
Thermal conductivity
Thermal grease

ABSTRACT

LED (light emitting diode) technology has been developed rapidly in recent years in the area of illumination applications. However, the rate of heat generation increases with the LED illumination intensity. The LED chip temperature is critical to determine the LED lifetime and efficiency. In this study, the thermal conductivities of grease mixed with four different nanoparticles – MWCNT (multi-walled carbon nanotube), silver, copper (II) oxide, and aluminum oxide (Al_2O_3) are measured by using a solid thermal conductivity measurement system. It is found that the measured thermal conductivities of the grease with MWCNT, silver, copper (II) oxide, and aluminum oxide enhance up to 82.8, 26, 58.8 and 40% at 1.0 wt%, respectively, compared with that of the pure grease. Results confirm that the MWCNT grease is the best candidate out of the four different nanoparticles-based greases for the LED package cooling performance.

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1. Introduction

As the environmental regulations like Kyoto protocol, Restriction of Hazardous Substance (RoHs), and WEEE (Waste Electrical and Electronic Equipment) are getting strengthened, it is critical to maintain processes and manufacture products more eco-friendly. The Kyoto protocol has restricted the use of FC (Fluoro-carbons) and HFC (hydro-fluoro-carbons) which cause the ozone depletion and global warming problems. The RoHs has banned new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, PBB (poly-brominated biphenyl) and PBDE (poly-brominated diphenyl ether) flame retardants on the EU market. WEEE aims to reduce the amount of electrical and electronic equipment being produced and to encourage reusing, recycling and recovering it. It also aims to improve the environmental performance of businesses that manufacture, supply, use, recycle and recover the tools. Therefore, there are many studies that have tried to resolve these problems. [1,2].

Typically LED (light emitting diode) is a kind of solid-state semiconductor devices that directly convert electrical energy into light. A high power LED has attracted great attention due to its significant impacts on solid-state illumination industry [3,4], and it is strong candidate for the next generation of general illumination applications [5,6]. The LED demonstrates a number of benefits compared to the traditional incandescent and fluorescent lamp. However, over 85% of electronic power of LED is converted into heat and this waste heat seriously reduces the efficiency of the device as equal as that of the luminosity in LED system. Also, the redundant heat will decrease the lifetime of the device. If the heat is not dissipated quickly form the P–N chip, the LED illumination intensity and lifetime will be significantly reduced. Therefore, effective thermal design with low thermal resistance for the LED packages is critical to improve the performance of LED [7–12]. To achieve the effective heat dissipation, a low thermal resistance between the LED chip and the heat spreader or between the heat spreader and the heat sink is also extremely important. For this purpose, highly conductive TIMs (thermal interfacial materials) must be applied to these interfaces. These materials are used to fill the grooves in the interfaces, effectively reducing the thermal contact resistance of these interfaces, and thus the heat conduction between the chip and the outside environment is enhanced. However, these TIMs do not have a high thermal conductivity enough to enhance the cooling performance of LED system [13].

At present, CNT (carbon nanotube) is one of the most actively studied materials due to its high aspect-ratio, mechanical strength, and good chemical and thermal stability [14,15]. Especially, CNT has a much higher thermal conductivity than metal or metal oxide nanoparticles. Therefore, CNT becomes a very valuable nano-scale

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0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.07.039

Nomenclatures

A	area [m^2]
L	length [m]
R'	overall thermal resistance [K/W]
R	conductance thermal resistance [K/W]
K'	overall thermal conductivity [W/mK]
K	thermal conductivity [W/mK]
$\dot{Q}$	heat transfer rate [W]
n	number of measurement
B	bias error
P	precision error
U	uncertainty

Subscripts

r	copper cylinder
x	measured sample
b	thin sample
d	thick sample
c	contact

material to improve the thermal conductivity of base materials. Xu and Fisher [16] synthesized a 10-μm thick aligned multiwalled carbon nanotube (VACNT) array on silicon and assembled a copper/VACNT/silicon TIM structure. They reported an overall resistance of 19.8 mm^2 K/W at 0.45 Pa measured by a reference method. Hu et al. [17] employed the combination of CNTs and traditional thermal conductivity fillers for TIMs. They reported a thermal conductivity value of seven times higher than that of the base material, approximately double thermal conductivity of the equivalent TIM composite with only conventional fillers. Kiran and Nanda [18] reported the enhancement of thermal conductivity of thermal grease used in cooling of electronic devices by the addition of multi-walled carbon nanotubes (MWCNTs). Thermal grease is generally used as a thermal interface material which increases the thermal conductivity of a thermal interface by filling air gaps present due to the imperfectly flat and smooth surfaces of the components.

In this paper, thermal enhancement of the grease based on silicon oil that is mixed with MWCNTs is studied, depending on the concentration of MWCNTs. The thermal conductivity of the grease is determined by using a heat flow meter. To confirm the significant enhancement of the thermal properties enabled by MWCNTs, three other nanoparticles are also mixed with the grease and tested for their respective thermal conductivity, including silver, copper (II) oxide, and alumina (Al_2O_3). The objectives of this study are to measure the thermal conductivities of the MWCNT grease, compared to the other additive pastes, and to evaluate the possibility to enhance the LED cooling performance by applying the nano-grease for actual LED lamp samples.

2. Experiment

2.1. Preparation for nano-greases

The nano-greases are prepared by a two-step method. First, base grease is stirred using a mechanical stirrer for 5 min. The thermal grease YG-6111(GE Toshiba Silicones co., Ltd., Japan) is used as the base grease in this study. Then, MWCNTs and three different kinds of nanopowders (Ag, CuO, and Al_2O_3) are added into the base grease, respectively, and mixed by using a mechanical stirrer at 200 rpm for 30 min.

The concentrations of MWCNT in the nano-grease were varied from 0.25 to 1.6 wt%. In case of the metallic and metal oxide nano-greases (Ag, CuO, and Al_2O_3), the concentration of nanoparticles was fixed at 1 wt%, to compare with the MWCNT nano-grease at 1 wt% that shows the best thermal conductive performance.

2.2. Experimental apparatus and procedures

To measure the thermal conductivity, a comparative cut bar method is used in this study. The comparative cut bar method is the most widely used method for axial thermal conductivity testing. In this method, a rod of the material with unknown sample is sandwiched in between a material with known conductivity on both of its ends. A heating element is then placed at one end of the setup, in a similar manner as in the absolute axial flow method, and the segment lengths and cross-section area are determined with the calculations involved. It is easy to operate and can measure all type of materials such as liquids, solids, and pastes [19].

Fig. 1 shows the schematic of experimental apparatus using the comparative cut bar method. The experimental apparatus consists of water storage, a reference sample and experimental sample. In this experiment, copper cylinders, reference samples with a diameter of 40 mm, are used. The upper, medium and low copper cylinders have different lengths. The heater is inserted into the upper copper cylinder, and the lower copper cylinder is cooled by the cooling water. Coolant (water) is kept at a constant temperature of 18 °C and is circulated by pump. An inverter control system is used to control the heat capacity and the coolant flow rate. Heat transfer occurs from the top to bottom of the test section. Heat loss from the test section to the surrounding is neglected because the cooper cylinder is completely covered by insulation material. Therefore, the heat transfer occurs only by conduction from the upper to the lower cylinder in this system. Then the prepared grease is dispensed into a cylindrical acrylic container. During the measurement, the reference sample and the grease sample are sandwiched between the copper cylinders. Table 1 summarizes the specifications of the grease, MWCNT, silver, copper (II) oxide, and alumina (Al_2O_3) nanoparticles used in the experiment. Table 2 summarizes the conditions of experimental equipment. Temperature is measured by RTD (Resistance Temperature Detector) sensor. Each temperature and input power is recorded for every second from the data acquisition equipment. Finally, the thermal conductivities of the pure grease and the mixture with additive materials are calculated using Fourier's equation from measured temperature gradient and heat flux at each point as shown in Fig. 1.

Fig. 2 shows the actual system of the high-power LED packages. This LED lamp has about 85 W capacity produced and packaged by JSA Global company. This lamp is originally designed by direct contact between the heat sink and LED package. The heat sink used in this sample is combined with a heat pipe and fins. Therefore the latent heat and convection are important factors in this heat sink.

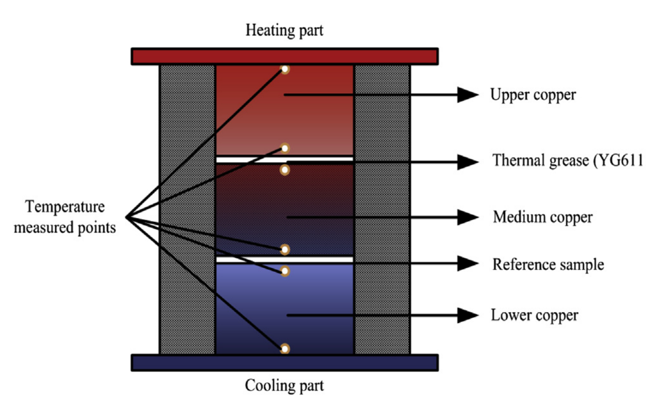

Fig. 1. Schematic diagram of the experimental apparatus.

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