Accurate measurement of LED lens surface temperature

Indika U. Perera, Nadarajah Narendran*, and Yi-wei Liu
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180 USA

ABSTRACT

Radiant power emitted by high power light-emitting diodes (LEDs) have been steadily increasing over the past decade. High radiation, especially short wavelength, can increase the temperature and negatively affect the primary lens performance of high-power LEDs. In this regards, assessment of lens temperature during operation is important. Past studies have shown large errors when thermocouples are used for measuring temperature in high radiant flux environments. Therefore, the objective of this study was to understand the problem in using thermocouples to measure LED lens surface temperature and to find a solution to improving the measurement accuracy. A laboratory study was conducted to better understand the issue. Results showed that most of the error is due to absorption of visible radiant energy by the thermocouple. In this study, the measurements made using an infrared (IR) thermal imaging system were used as the reference temperature because the IR imaging system is unaffected by radiant flux in the visible range. After studying the thermocouple wire metallurgy and its radiation absorption properties, a suitable material was identified to shield the thermocouple from visible radiation. Additionally, a silicone elastomer was used to maintain the thermal interface between the lens surface and the thermocouple junction bead. With these precautions, the lens temperature measurements made using the J-type thermocouple and the IR imaging system matched very well.

Keywords: light-emitting diode, lens surface temperature, thermocouple, IR thermal imaging system, thermocouple shielding

1. INTRODUCTION

The gallium nitride (GaN) based light-emitting diode (LED) technology has improved significantly over the past decade and now emits high radiant power, of the order of watts per chip. Past studies have reported shortened LED package life due to encapsulant degradation caused by high temperature [1],[2]. High radiation, especially short wavelength, can increase the temperature of the primary lens due to absorption [2]. To minimize lens degradation and improve LED performance, it is necessary to measure the lens temperature accurately during operation. Past studies have shown large measurement errors when using thermocouples in high visible radiant flux environments [3],[4]. Therefore, the objective of this study was to understand the problem in using thermocouples to measure LED lens surface temperature and to find a solution to improving the measurement accuracy.

A thermocouple consists of two electrical conductors that are made of dissimilar metals [5]. These electrical conductors are joined together by either welding or soldering, ensuring good electrical contact at the junction. When the temperature at the thermocouple junction increases, a voltage difference is induced across the ends of the two conductors. This voltage difference is related to the temperature at the junction and the electrical properties of the two conductors. Measuring temperature with the use of a thermocouple is very common and is classified as an intrusive measurement [5]. Measurement errors can be caused by thermocouple geometry, insertion, and heat transfer interactions [5]. Several photometric measurement standards, even though they do not explain the reason, recommend shielding the thermocouple from direct radiation [6].

Based on the findings from past literature, it was hypothesized that the visible radiation from the LED is absorbed by the thermocouple junction and the lead wires, causing large errors in the temperature measurements. Figure 1 indicates radiant flux from an LED package irradiating the thermocouple junction and the lead wires. In addition, energy is transferred to the thermocouple junction via conduction from the primary lens. The figure shows the radiative and convective cooling to and from the ambient environment of the thermocouple junction and the wire leads.

*Corresponding author: +1 (518) 687-7100; narenn2@rpi.edu; http://www.lrc.rpi.edu/programs/solidstate/

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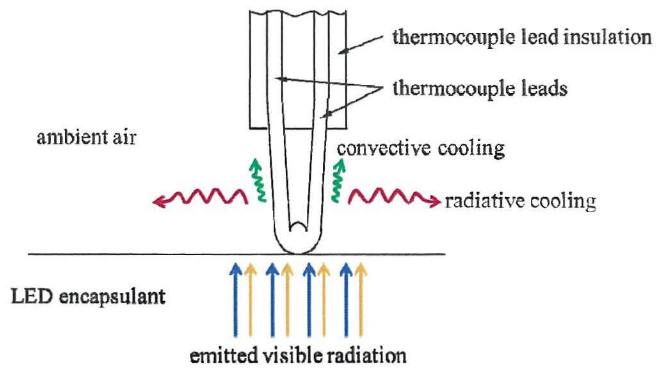

Figure 1. Sketch illustrating the energy transfer between thermocouple, LED lens medium and ambient environment in a high visible radiant flux environment

The J-type thermocouple, a commonly used thermocouple type for measuring temperature, has its positive lead wire metallurgical composition as 99.5% iron and the negative lead metallurgical composition as 55% copper and 45% nickel [7]. Figure 2 shows the absorption spectra for these three metals, adopted from Touloukian and DeWitt [8]. The figure indicates high absorption of visible radiation between 380 to 780 nm wavelength, indicated by the vertical dashed lines, compared to long-wavelength infrared (IR) radiation.

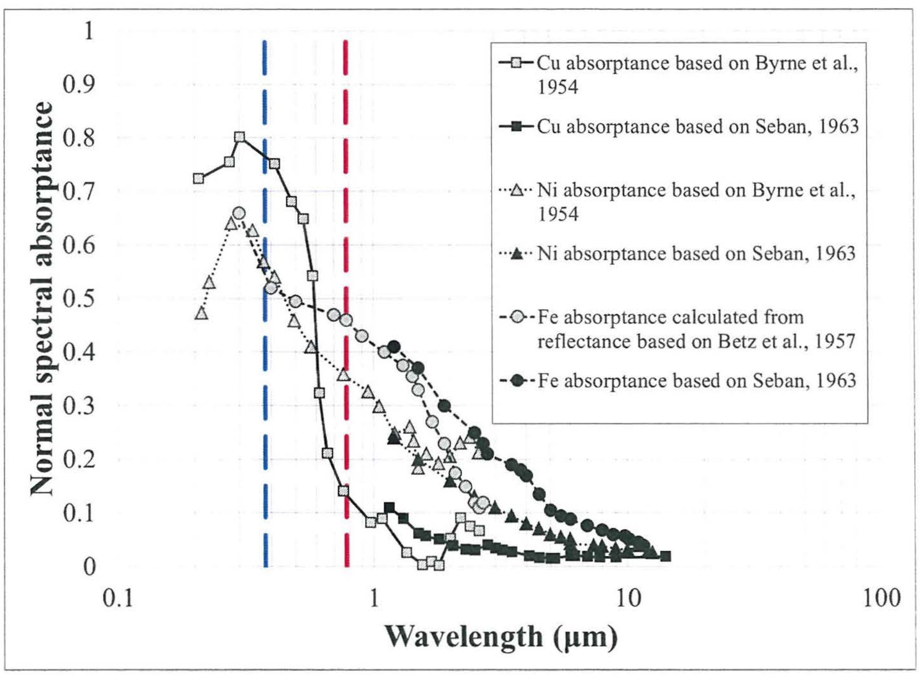

Figure 2. Absorption spectra of metals commonly used for thermocouple leads, adopted from [8]

2. INFRARED THERMOMETRY FOR TEMPERATURE MEASUREMENT

Infrared (IR) thermometry has been used in the electronics and LED industries to measure surface temperatures as an alternative to intrusive thermocouple temperature measurements [9],[10]. Equipment spectral sensitivity, calibration, and knowledge of the target surface emissivity becomes important in obtaining accurate and repeatable measurements with IR thermometric equipment [9],[10]. Generally, IR thermographic systems are designed to be spectrally sensitive in 3-5 μm and 7-14 μm wavelength ranges [10]. Since IR thermographic equipment is not sensitive to the visible spectrum (0.38-0.78 μm), it is an ideal reference sensor for measuring the surface temperature of an LED primary lens [10].

An IR imaging camera with a spectral sensitivity range of 7.5-14 μm was used in this study. To determine the temperature of a target surface accurately using IR thermography, the surface emissivity of the target needs to be determined [10]. A preliminary experiment was conducted to estimate the LED primary lens surface emissivity based on the recommended practices in the IR thermometric community [10].

An experiment was conducted to verify the hypothesis, in which the thermocouple-measured temperature would have a positive error in a visible radiant flux environment, while both the thermocouple and the IR imaging method would provide similar temperature measurements if there was no visible radiant flux on the thermocouple. A multi-chip LED package with a single primary lens attached to a heat sink was used in this experiment.

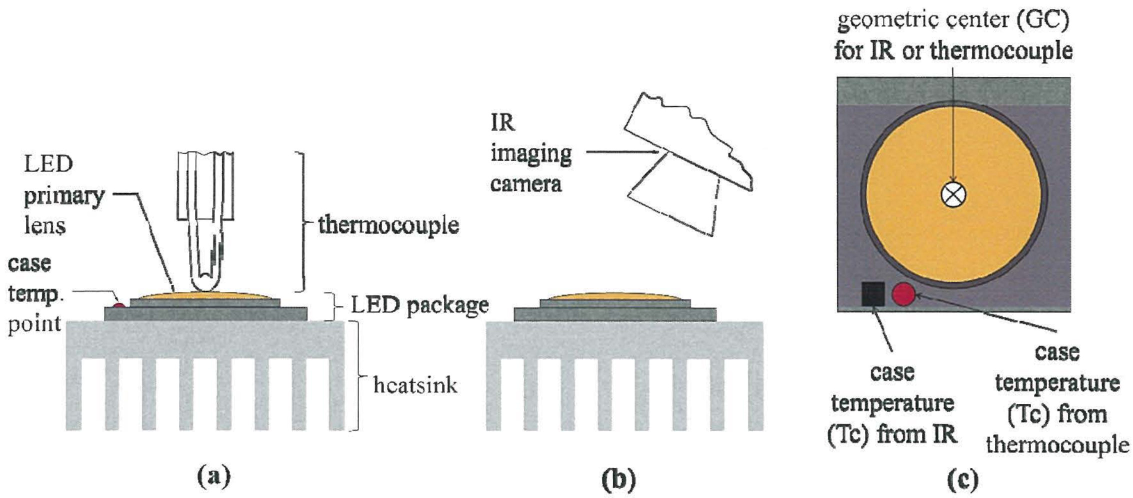

Figure 3. Sketch of the experimental setup: (a) thermocouple location on geometric center of the LED package primary lens; (b) IR imaging camera; (c) plan view of the LED package with geometric center and case temperature measurement locations

Figure 3 shows the location where a thermocouple was attached to the case temperature (Tc) location, with the use of thermal epoxy for measuring case temperature. A 5×5 mm^2 square of general purpose black electrical tape was adhered on to the LED package board as the reference for the IR temperature measurement at the case temperature location, as illustrated in Figure 3. A J-type thermocouple and the IR imaging camera were used alternatively to measure the LED package lens geometric center (GC) temperature. No thermal interface material was used for the thermocouple measurements at the LED package's geometric center. The LED package primary lens surface emissivity was assumed to be 0.97 based on past experiments.

Table 1 shows the results of this experiment where the thermocouple-measured and the IR imaging camera-measured temperatures at the case temperature (Tc) location were similar. However, the geometric center (GC) temperature measurement was higher with the thermocouple.

Table 1. LED package lens geometric center temperature and case temperature measured with J-type thermocouple and IR imaging camera. The numbers within parentheses indicate the deviation of the thermocouple temperature measurement from the IR imaging camera-measured temperature.

Drive current (mA)	**IR @ GC avg. temp. (°C)**	**Thermocouple @ GC avg. temp. (°C)**	**IR @ Tc avg. temp. (°C)**	**Thermocouple @ Tc avg. temp. (°C)**
300	51.8	55.4 (+7%)	47.0	47.2 (+1%)
700	81.3	90.1 (+11%)	83.6	84.8 (+1%)
1000	100.1	110.5 (+10%)	47.0	47.2 (+1%)

3. SHIELDING OF THERMOCOUPLES

In the previous experiments, the thermocouple radiation error was observed and the ability of IR thermographic techniques to measure the temperature was demonstrated. In order to find a method to reduce the thermocouple absorption of visible radiation emitted by the LED package, the use of highly reflective, commercial grade pipe thread sealant polytetrafluoroethylene (PTFE) (≥99%) material for shielding thermocouple lead wires was investigated.

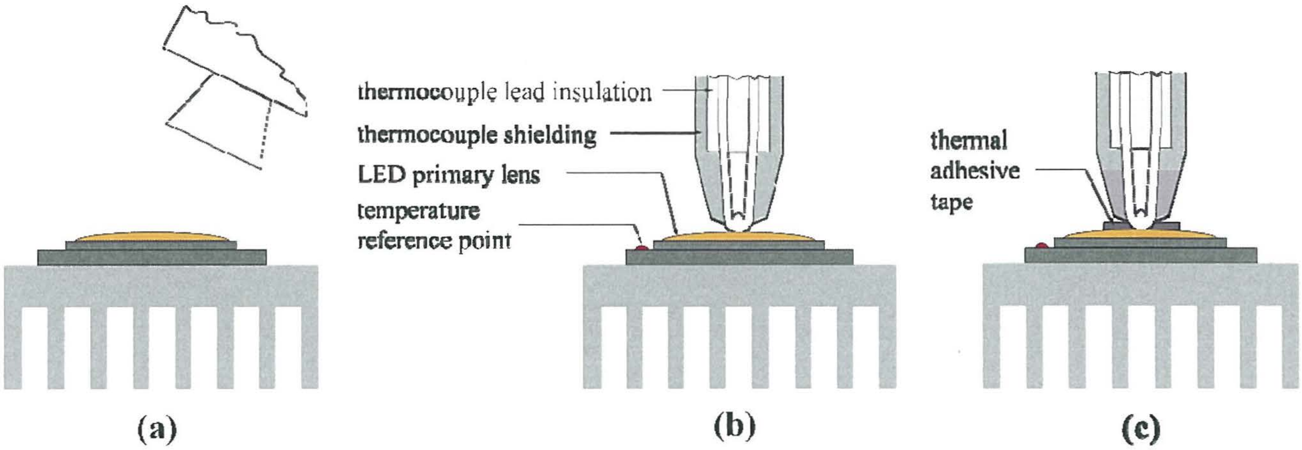

Figure 4. Sketch of experimental setup for IR and thermocouple measurement: (a) IR imaging measurement; (b) thermocouple lead wire shielding with PTFE; (c) same as (b) with thermal adhesive tape as a thermal interface material

As shown in Figure 4, the PTFE material was used to wrap the thermocouples from the junction to a length sufficient enough to shield the thermocouple lead wires from being exposed to visible radiation emitted from the LED primary lens. The thermocouple junction was left exposed in order to minimize the negative error from increasing the thermal resistance between the LED package primary lens surface and the thermocouple junction. The shielded thermocouples were calibrated for 0°C and 100°C to ensure the shielding process did not alter the basic operation of the thermocouples.

In order to improve the heat conduction between the thermocouple junction and the LED package lens surface, a square strip of 2×2 mm^2 white thermal adhesive tape was used, as illustrated in Figure 4(c). The thermocouple junction was pressed into the thermal adhesive tape, as indicated in the figure above, to thin out the thermal adhesive tape and have the thermocouple junction embedded in the thermal tape. The IR imaging camera was used as the reference temperature measurement.

Table 2 shows the temperature measurements from the PTFE-shielded thermocouple with thermal adhesive tape and from the IR imaging camera at the geometric center of the LED package lens surface. The thermocouple measurements were similar to the IR imaging camera-measured temperatures within ±3°C. The numbers within parentheses indicate the deviation of the thermocouple measurements from the IR imaging camera-measured temperature values.

Table 2. Temperature measurement with thermocouples with PTFE shielding and thermal tape

Drive current (mA)	**GC temp. with IR imaging (°C)**		**GC temp. with thermocouple with PTFE shielding and thermal tape (°C)**	
	Avg.	**Std. Dev.**	**Avg.**	**Std. Dev.**
160	36.3	0.5	36.8 (+2%)	1.2
780	71.9	0.3	73.9 (+3%)	0.6
1100	93.0	0.7	92.9 (-1%)	0.6

4. ALTERNATIVE THERMAL INTERFACE MATERIALS WITH PTFE-SHIELDED THERMOCOUPLES

In order to check the effect of the thermal adhesive tape on the thermocouple measurement, an optically clear silicone elastomer was used as an alternative thermal interface material. Figure 5 shows the use of optically clear silicone elastomer as an alternative thermal interface material. Due to the use of thermal interface material, the LED package lens surface had to be cleaned after every measurement; therefore, the thermocouple measurements were repeated multiple times with different thermocouples to check repeatability as well. To ensure that the operation of the thermocouples were not compromised after the PTFE shielding process, the shielded thermocouples were calibrated at 0°C and 100°C. The IR imaging camera was used as the reference measurement.

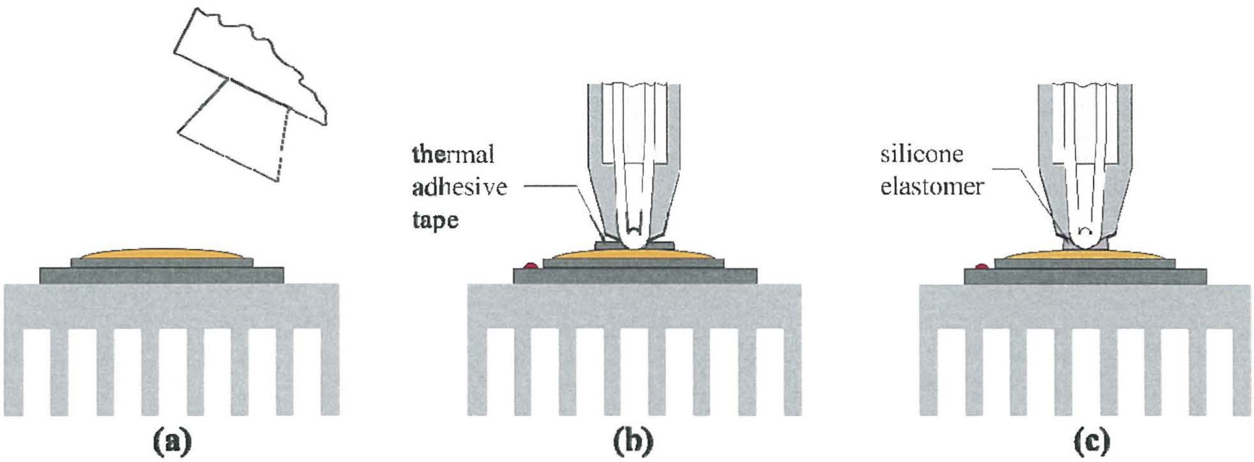

Figure 5. Sketch of the experimental setup: (a) IR imaging measurement; (b) PTFE shielding with thermal adhesive tape; (c) PTFE shielding with silicone elastomer

The results from this experiment are shown in Table 3. The deviation of the thermocouple measurements from the IR imaging temperature measurements are shown within parentheses in the table below. The PTFE shielded thermocouples with thermal adhesive tape and silicone elastomer both measured similar temperatures with deviations of less than +3% from the IR imaging-measured temperatures. The results also illustrated the repeatability of the shielding method with multiple thermocouples.

Table 3. Temperature measurements with PTFE-shielded thermocouples with alternative thermal interface materials

Thermocouple No.	Test No.	IR imaging temp. (°C)	PTFE-shielded thermocouple with thermal tape temp. (°C)	PTFE-shielded thermocouple with silicone temp. (°C)
1	1	96.2	98.1 (+2%)	
	2	96.4		98.2 (+2%)
2	3	96.7	97.7 (+1%)	
	4	96.5		97.3 (+1%)
3	5	96.1	96.8 (+1%)	
	6	96.3		98.7 (+2%)

5. DISCUSSION

The use of unshielded thermocouples to measure primary lens surface temperatures would result in higher measured values due to the absorption of visible radiation emitted by the LED package. IR thermography can be used to accurately measure the lens surface temperature provided that the spectral sensitivity of the IR measurement equipment is not affected by the visible radiant flux of the LED package, the equipment is properly calibrated, and the surface emissivity of the primary lens material of the LED package is known. It was experimentally shown that with proper use of IR thermometry, accurate measurement of LED package lens surfaces is possible. The absorption of visible radiation introduces error, which can be reduced by using a highly reflective thermal insulating material to shield the thermocouple lead wires. The measurement error of these shielded thermocouples with either optically clear silicone elastomer or white thermal tape was within ±3°C of the IR imaging temperature measurement.

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