Thermal Analysis of high power LEDs using different PCB materials

Shusmitha Kyatam[1,2]*, **Pedro Camacho**[1,2], **Luís Rodrigues**[1,2], **Luís Nero Alves**[1,2], **Joana Catarina Mendes**[1,3], **Mónica Carvalho Figueiredo**[1,4]

[1] Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[2] Department of Electronics, Telecommunications and Informatics, University of Aveiro, 3810-193 Aveiro, Portugal
[3] Centre for Mechanical Technology and Automation, University of Aveiro, 3810-193 Aveiro, Portugal
[4] Department of Electrical Engineering, Polytechnic Institute of Leiria, 2411-901 Leiria, Portugal
* shusmithakyatam@gmail.com

***Abstract* — Visible Light Communication is an emerging technology in Optical Wireless Communication where the Light Emitting Diodes (LEDs) are utilized for transmission of data. The luminance of the LEDs increases with the forward current; however, for high current levels the heat generated by non-radiative recombination of carriers increases the LED junction temperature, decreasing the efficiency and the lifetime of the devices. Therefore, the design of high power LED driver circuits needs to take into account the unavoidable local heating produced by high power components. In this paper, we performed thermal analysis of an LED driver mounted on Printed Circuit Boards (PCBs) using Thermal Risk Management (TRM) software and studied the heat dissipated by various components on PCBs composed of different dielectric materials such as FR4 and Diamond. Based on TRM simulations, the replacement of FR4 with diamond caused the junction temperature to decrease from 64°C to 45.2°C for a forward current level of 350 mA. The replacement of FR4 with diamond thus effectively improves the thermal management of LEDs and corresponding driver circuits.**

Keywords— Thermal Management, Junction Temperature, Visible Light Communication, Light Emitting diodes, Diamond.

I. Introduction

The role of wireless communications in modern society is becoming more and more important, from private to business and safety applications. Broadband wireless services such as HDTV, computer network applications, mobile phones, video conferencing or high-speed Internet access have undergone a fast growth over the past decades, leaving Radio Frequency (RF) spectrum fully occupied, thus demanding alternatives for RF communications [1].

Visible Light Communication (VLC) is a field of optical wireless communications that utilizes visible light to transmit data [2]. The developments on high-brightness white LEDs contributed to the improvement of lighting systems; in addition these components, show faster modulation capability. VLC technology has the benefit of the unregulated high bandwidth availability, high data rates due to LED high modulation capability, absence of electromagnetic interference, improved security and lower power consumption [1,3]. Using white LEDs for both communication and illumination will further increase systems efficiency.

Similar to normal diodes, an LED is a junction of P-type and N-type semiconductor materials. When such a junction is formed, majority carriers flow to both sides of the junction, leaving behind a depletion region of free carriers. When a forward voltage is applied across the junction, it accelerates electrons and holes from the neutral regions of the semiconductor and injects them into a region with opposite conductivity. During this process, pairs of electrons and holes "meet" at the depletion region, where they recombine, emitting a photon with an energy equivalent to the semiconductor bandgap. If the frequency of the emitted photon falls in the visible range, this phenomenon is termed as luminescence reaction and the emitted optical energy is called luminous flux [7]. In an ideal LED, all the electron-hole pairs recombine and all the electric power is converted into optical power. However, in real devices, some carriers lose their energy to the crystal lattice in the form of phonons (heat). In addition, some unwanted mechanisms may prevent the produced photons from leaving the LED die (reabsorption of the light in the substrate of the LED on in the metal contacts or even total internal reflection). As a result, part of the electric power is converted to thermal energy, thereby the LED junction temperature increases. This parameter is essential in determining both the lifetime and luminous flux of the LED. Hence, an effective thermal management is essential in order to maintain the junction temperature at acceptable levels. Since the LEDs performance is influenced by the operating temperature, the fabrication of an efficient LED system requires a basic understanding of the thermal phenomena involved. In addition to the temperature increase inherent to the LED operation, the power dissipated on the electronic components of the LED driver itself may also contribute to the increase of the PCB temperature – and the system designer should take all these factors into consideration.

In the present work we have analyzed the thermal profile of a PCB with a LED and corresponding driver circuit. In order to get an insight of the influence of the PCB material, two substrates with completely different thermal conductivities were chosen, FR4 and diamond. Diamond has the highest known thermal conductivity at room temperature (with the exception of graphene [4], a 2D material not suitable to be used directly as a PCB); diamond substrates can easily be fabricated by Chemical Vapor Deposition (CVD) [5]. Metallized diamond plates, ready for the mounting of SMD devices, can currently be purchased from a few vendors around the world. Being a material with such a high conductivity, a diamond plate behaves like a "thermal short circuit" and could, under the right

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conditions, replace the bulky heat spreaders currently needed for high power applications. This could be an advantage, for instance, for aeronautics and space applications, where the volume and weight of the electronic modules should be as small as possible. However, presently the diamond plates are quite expensive (typically 300€ for a 300 µm-thick 10×10 cm^2 plate, in addition to metallization costs) and, as such, the advantages in terms of life time and circuit efficiency should be quantified prior to the generalized use of this material as a PCB.

The paper is organized into following sections: the LED driver circuit is briefly presented in section IIA, followed by the discussion of the theoretical dependence of diode forward voltage and saturation current with temperature (section IIB); section III presents the advantages of using diamond as a thermal conductor; simulations obtained with Thermal Risk Management (TRM) software are presented in section IV; the results are presented in the section V and finally Section VI consists of the conclusions.

II. Thermal Analysis of the PCB

A. PCB with LED and corresponding driver

The LED driver is an electrical circuit that controls the input power to the LED. It increases the lifetime of the LED by regulating its operating environment. In this scenario the driver biases the LED and controls the applied modulating voltage. It works as a voltage buffer between the modulating voltage source and the LED producing voltage gain to suit the LED needs. Furthermore, it acts as an impedance matching network. This voltage modulation is directly related to the current change in the LED, which translates in a change of luminous intensity emitted by the LED.

Temperature plays an important role in the LED lifespan: lower operating temperatures guarantee a longer lifetime. To improve the heat dissipation, a large copper pad was connected to the heatsink pad of the LED. The sizes of the pad and PCB are inversely proportional to LED operational temperature. However, space limitation is a problem in the current setup, and common PCB materials require larger footprints for improved heat dissipation. A compromise solution would be to find a material with higher thermal conductivity, allowing for smaller footprints.

B. Dependence of LED junction temperature with external voltage

Upon operation, the luminous flux of the LED should be as stable as possible. However, for a given current, the voltage drop across the diode depends on the temperature – which should be as stable as possible during the LED operation.

The LED junction temperature T can be obtained from the I-V characteristics using the method described in [6]. The current density J that flows through a p-n junction is related with the applied voltage V by the Shockley equation:

$$J = J_s\left[exp\left(\frac{eV}{nk_BT}\right) - 1\right] \tag{1}$$

where J_s is the saturation current density, e is the electron charge, n is the ideality factor, k_B is the Boltzmann constant and T is the junction temperature. When the voltage applied in forward bias V_f » $\frac{kT}{e}$ eq. (1) can be approximated by:

$$J_f = J_s\left[exp\left(\frac{eV_f}{nk_BT}\right)\right] \tag{2}$$

Note that in the last equation the effect of the series resistance is not considered and, as a consequence, the voltage drop at the junction corresponds to the external voltage V_f, which can be obtained by solving eq. (2):

$$V_f = \frac{nk_BT}{e}\ln\left[\frac{J_f}{J_s}\right] \tag{3}$$

Differentiating voltage with respect to temperature, we get:

$$\frac{dV_f}{dT} = \frac{d}{dT}\left[\frac{nk_BT}{e}\ln\left[\frac{J_f}{J_s}\right]\right] \tag{4}$$

By taking into account the temperature dependence of the intrinsic carrier concentration n_i and of the effective densities of states at conduction and valence bands N_C and N_V, respectively, one obtains [4]:

$$\frac{dV_f}{dT} = \frac{eV_f - E_g}{eT} - \frac{3k_B}{e} + \frac{1}{e}\frac{dE_g}{dT} \tag{5}$$

This equation describes the fundamental dependence of the forward voltage with junction temperature. The first term on the right-hand side of the eq. (5) is related with the temperature dependence of intrinsic carrier concentration. The second term reflects the temperature dependence of N_C and N_V. The last term is related with the temperature dependence of bandgap energy (E_g), which can be given by the Varshni formula [6]:

$$E_g = E_0 - \frac{\alpha T^2}{T+\beta} \tag{6}$$

where α and β are the Varshni parameters. Substituting eq. (6) in eq. (5) finally yields:

$$\frac{dV_f}{dT} \approx \frac{k_B}{e}\ln\left[\frac{N_DN_A}{N_CN_V}\right] - \frac{\propto T(T+2\beta)}{e(T+\beta)^2} - \frac{3k_B}{e} \tag{7}$$

The Varshni parameters of different semiconductors are given in Table I [7]. Including the series resistance, the values predicted by eq. (7) would change 24% for GaN, 29% for GaAs, and 15% for Si. This last equation gives an estimate of the temperature coefficient with the junction voltage.

The current that flows under reverse bias, referred to as the saturation current, is due to the diffusion of minority carriers from the neutral regions to the depletion region; it is also temperature dependent, however this dependence is not straightforward. J_s can be expressed as:

$$J_s = e\left[\sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_D} + \sqrt{\frac{D_p}{p}}\frac{n_i^2}{N_A}\right] \tag{8}$$

where D_n and D_p are the diffusion constants of electrons and holes and τ_n and τ_p are the minority carrier lifetimes of electrons and holes, respectively. In case of phonon scattering, the diffusion constants show a $T^{-1/2}$ dependence. The carrier lifetimes can decrease (in the case of nonradiative recombination) or increase (in the case of radiative recombination) with temperature. As such, a closed relation between the dependence of the reverse current density with temperature cannot be easily obtained [7].

TABLE I. VARSHNI PARAMETERS OF DIFFERENT SEMICONDUCTORS [7]

Material	E_g at 0 K (eV)	α (10^{-4} eV/K)	β (K)	Validity range
AlN (wurtzite)	6.026	18.0	1462	T ≤ 300 K
GaN (wurtzite)	3.47	7.7	600	T ≤ 600 K
GaP	2.34	6.2	460	T ≤ 1200 K
GaAs	1.519	5.41	204	T ≤ 1000 K
GaSb	0.813	3.78	94	T ≤ 300 K
InN (wurtzite)	1.994	2.45	624	T ≤ 300 K
InP	1.425	4.5	327	T ≤ 800 K
InAs	0.415	2.76	83	T ≤ 300 K
InSb	0.24	6.0	500	T ≤ 300 K
Si	1.17	4.73	636	T ≤ 1000 K
Ge	0.774	4.77	235	T ≤ 700 K

III. DIAMOND AS A THERMAL CONDUCTOR

As the forward current increases, the junction temperature also increases and efficient heat removal methods are required. The main goal is keep the LED junction temperature below a certain value, which is 150°C for most of the commercially available high power LEDs. The use of PCBs with high thermal conductivity is one of the best solutions to efficiently dissipate the heat generated in the vicinity of the LED junction.

TABLE II. PROPERTIES OF DIAMOND IN COMPARISON WITH OTHER SEMICONDUCTORS

Property	Silicon	Silicon Carbide	Gallium Nitride	Diamond
Bandgap (eV)	1.11	3.26	3.39	5.47
Breakdown field (MV/cm)	0.3	3.5	3.4	10
Thermal conductivity (W/(cm-K)	1.5	4.9	2	21.3

The availability of metallized CVD diamond plates opens the possibility of using this material to replace standard PCBs. Single crystal diamond has all the properties required to make it attractive for the thermal management of high power / high temperature electronic devices: high thermal conductivity (~2000 W/(m-K)), high band-gap (~5.4 eV) and high breakdown field (~2×10^7 V/cm) [5]; however, it is not available in large area substrates. CVD diamond, on the other hand, can be deposited in the form of plates while keeping a thermal conductivity between 1000-1600 W/(m-K). Diamond films also show excellent chemical resistance. Due to their intrinsic properties, they can be used as heat sinks in power electronic applications, increasing the efficiency and the lifetime of the devices. The properties of diamond and other wide bandgap semiconductors are listed in Table 2.

IV. THERMAL SIMULATIONS OF LED PCB USING TRM

TRM ("Thermal Risk Management") is a software developed by Adam Research group, Germany [8] designed to perform thermal analysis of PCBs. It calculates the detailed board temperatures for given operating conditions. The components temperature is calculated based on the components power and electric current. The thermal analysis of the PCB is performed by importing the Gerber files of each layer, PCB component files and drill data files to TRM. TRM solves temperatures on a lateral scale by about 200; the accuracy of temperatures agrees within ± 5% with infrared thermography if the currents, power and environment conditions are matching.

In order to evaluate the influence of the PCB material on the heat dissipation of the LED and corresponding driver, the thermal simulations were performed on PCB with copper as the conductive layer and FR4 or diamond as the dielectric material for different electric powers. The results obtained with FR4 as the dielectric material were then compared with infrared (IR) temperature measurements performed with an IR camera.

V. SIMULATION AND EXPERIMENTAL RESULTS

The LED and driver circuit were mounted on a FR4 PCB board; the 127 µm-thick board was 37.8 mm×24.4 mm in area (Fig. 1a). The LED was operated at 25°C room temperature. The surface temperature of the different components was measured with an IR camera (Fig. 1b); under these conditions the LED temperature was as high as 123°C. The thermal profile of the FR4 circuit board at 700mA forward current and 25ºC room temperature was obtained with TRM (Fig. 1c); the LED case temperature reached 104.6°C. The difference between simulated and measured values might be related with an increase of the ambient temperature when the measurements were performed. Fig. 1d shows the simulated thermal profile of the circuit mounted on a diamond PCB; in this case the temperature distribution on the PCB was uniform and the LED temperature was reduced to 68.4°C for a forward current of 700 mA when the dielectric was diamond, in comparison to 104.6°C when FR4 was used.

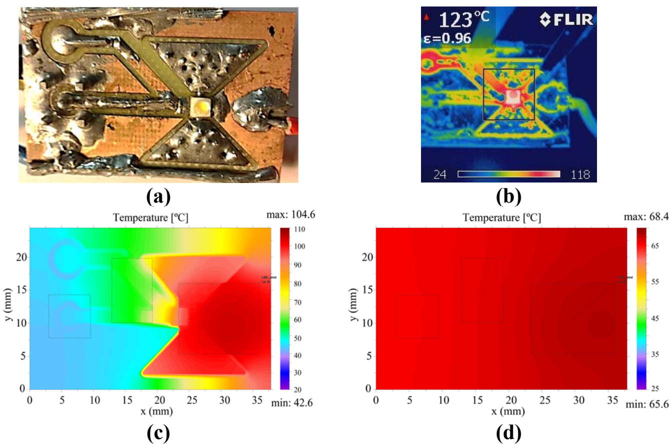


Fig 1: (a) LED PCB Board. (b) IR image of LED circuit (123°C at 700 mA); (c) Simulated board temperature with FR4 (104.6°C at 700 mA; (d) Simulated board temperature with diamond (68.4°C at 700 mA).

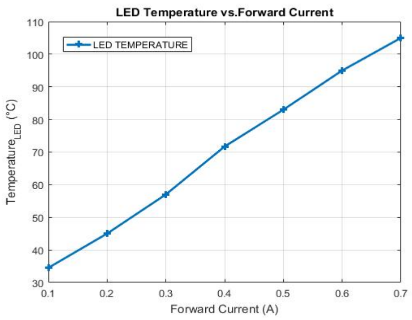
Table III shows the temperature of the LED case measured with the IR camera for different power levels. As expected, the LED temperature increases with increasing current levels.

TABLE III. LED TEMPERATURE FOR FR4 AND DIAMOND PCB

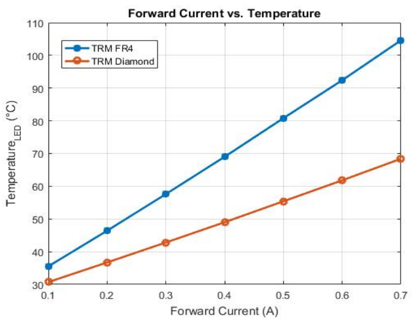
#	Current (A)	Power (W)	T_{LED} (°C) (IR camera)	T_{LED} (ºC)	
				TRM (FR4)	TRM (diam.)
1	0.1	0.292	34.78	35.5	30.7
2	0.2	0.596	45.38	46.4	36.7
3	0.3	0.909	54.32	57.6	42.8
4	0.4	1.228	69.73	69	49
5	0.5	1.555	83.49	80.8	55.4
6	0.6	1.878	95.28	92.4	61.8
7	0.7	2.219	109.16	104.6	68.4

The temperature of the LED calculated using FR4 and diamond PCBs for the same power levels using TRM can also be seen in table III. The temperatures measured with the IR camera and the TRM are in close match.

Fig. 2a plots the measured LED temperature as a function of the forward current level. Fig. 2b shows the simulated LED temperature as a function of the forward current level for both FR4 and diamond dielectric layers.



(a)



(b)

Fig 2: (a) Measured LED temperature versus forward current; (b) Simulated LED temperature versus forward current for FR4 and diamond dielectric layers.

VI. CONCLUSIONS

The reduction of the junction temperature of a LED has a positive impact both in the efficiency and lifetime of the device and, as such, the implementation of strategies to efficiently remove the excess heat is of paramount importance. Due to its intrinsic properties, diamond is one of the best candidate materials to be used as a heat sink. In this paper we present an approach where a metallized diamond plate is used as a PCB. The impact that this material may have in the operating temperature of an LED is analyzed for different current levels using TRM software and compared to the temperature obtained with a common FR4 PCB. For a current level of 350 mA, the LED temperature is expected to decrease from 64 and 45.2°C when FR4 is replaced with a diamond plate. It can be concluded that the use of diamond plates can be an alternative approach to improve the thermal management of high power LEDs.

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