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Measurement of the thermal characteristics of packaged double-heterostructure light emitting diodes for space applications using spontaneous optical spectrum properties

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Abstract

In this paper, the thermal characteristics of packaged infrared double-heterostructure light emitting diode (DH-LED), used in space applications, are measured under conditions that reproduce space environments. The characterisation uses spontaneous optical spectrum characteristics, current–voltage curves and optical power measured under a primary vacuum ($<10^{-2}$ Torr) at temperatures between −30 and 100 °C. The investigations have been specifically oriented toward the extraction of junction temperature in the steady-state regime and junction-to-case thermal resistance. A specific model based on semiconductor theory for electrical transport has been used to calculate the shape of the spontaneous emission spectrum between the band-gap energy and higher energies and its change versus temperature. A linear relation between the junction temperature and the dissipated power has been found for various case temperatures appropriately controlled in a LN_2 cryostat. These results confirm that thermal behavior of DH-LEDs depends on both environment temperature and dissipated power level in the active zone and that the junction-to-case thermal resistance is not constant over a large range of temperatures, diminishing at higher currents as already reported by recent papers on high brightness DH-LED. Finally, this study could represent a practical non-destructive method providing qualitative information about variations of junction temperature and junction-to-case thermal resistance taking into account an industrial qualification framework approach based on electroluminescence analysis, frequently measured by manufacturers or end-users.

Keywords: Light emitting diode; Junction temperature; Thermal resistance

1. Introduction

Photonic sub-systems are increasingly used in aerospace applications. Many require highly reliable solid-state light emitters such as light emitting diodes (LEDs). Examples of intra-satellite applications for such devices include optical interconnections, emitters in optocouplers, optical sensors and calibration sources for CCD detectors. However, these LEDs must survive in harsh environments such as space radiation but also operate under rougher environmental conditions (large temperature variations, high DC current, etc.). Moreover, in many cases, LEDs are placed in confined spaces. Heat management is one of the most important factors in these applications because of systematic elimination of thermocooler systems.

As is widely known, the lifetime of such devices is mainly determined either by their thermal management in steady state or by controlling the powering and cooling of the appliance in transient regimes. The transient regime has been widely studied, in particular for high power semiconductor LEDs [1].

The study reported here is oriented toward the estimation of junction temperature in the steady-state regime and toward the estimation of the junction-to-case thermal resistance. This last parameter is still of interest in semiconductor design and thermal analysis because packaged LEDs have a sandwich-like heat-removal path

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consisting of different materials and the thermal behavior is still difficult to define and estimate [2]. Indeed, all functional parameters of LEDs are directly or indirectly junction temperature (T_j) dependent. In particular, output optical power and central wavelength are critical parameters for optoelectronic transmitter devices regarding both operating conditions and reliability during a space mission. The junction temperature is a physical variable affecting internal quantum efficiency, current density, carriers and photon lifetime, is responsible for optical power drift and more generally affects the reliability of the LED device. In the case of packaged LEDs and for high junction temperature ($\approx 150\,^\circ$C), the materials used can be deteriorated by:

- the coefficient of thermal expansion mismatch of each material,
- a temperature exceeding the vitreous transition value for encapsulated materials.

These mechanisms are generally responsible for the catastrophic damage of LEDs performances [3]. Moreover, due to the recent huge growth in the field of optoelectronics, novel devices and related technologies are continuously being introduced. However, underlying this progress is a risk until thorough verification of qualification is completed. Thus, a key point deals with the accurate determination of the junction temperature and thermal resistance of an LED during qualification tests for a given technology. For example, the central wavelength increases of about 0.1–0.5 nm/°C for both DFB laser diodes [4] and double-heterostructure (DH)-LEDs [5,6]. In this case, the thermal management of packaged LEDs is decisive to provide the overall performance of the device. So validation of the thermal design and assembly repeatability as well as semiconductor stability involve the ability to measure the junction temperature.

2. Context and objectives

Various techniques and models have been proposed for LED junction temperature measurement or calculation. A number of papers have reported significant results obtained using techniques including threshold voltage [7], micro-Raman spectroscopy [8], photo-thermal reflectance microscopy [9], thermal resistance [10], electroluminescence [11], and photoluminescence [12], a non-contact method [13] and a nematic liquid crystal with IR laser illumination [14]. Raman spectroscopy needs a sophisticated experimental setup with a limited accuracy for a well-cleaved surface ($\pm 10\,^\circ$C). Electroluminescence and photoluminescence cartographies are also limited in accuracy and unpractical on packaged devices. Photo-thermal reflectance microscopy is difficult to use for packaged LEDs. The non-contact method uses the emission peak ratio of dichromatic LEDs and thus cannot be applied for monochromatic LEDs as considered in our paper. The threshold voltage method takes into account the temperature coefficient of the diode forward voltage and the emission peak energy [15]. This method is highly sensitive and its accuracy is estimated to be $\pm 3\,^\circ$C. This technique is well known to provide measurements of junction temperature allowing an assessment of the reliability of the component in the final environment, but is less efficient regarding failure mechanism identification.

Theoretical work on optical spectrum modeling of spontaneous emission in DH-LEDs has been previously reported. Some papers have recently introduced the nonparabolicity of the GaAs conduction band (CB) [16], showing the impact of the internal electrical field, used to calculate the state densities in a photonic semiconductor [17]. For example, Garcia-Botella et al. have reported the effect of temperature on the optical spectrum of surface mounted LEDs between 0 and 40 °C. They proposed a semi empirical model based on solid-state theory including a nonparabolic approximation for the densities of state and the Varshni relation for the gap temperature dependence [18]. However, such models provide a complex fit of the optical spectrum gaussian shape of spontaneous emission in the case of DH-LEDs because of the difficulty to estimate the physical parameters of the nonparabolicity band structure. Moreover, it was also demonstrated that deviations of the exponent parameter on the energy from the parabolic approximation for the density of states calculations are low. Estimated physical parameters as well as photometric and radiometric behavior for the semi empirical model fitting the experimental data have been computed but no information about the junction temperature is provided.

In a recent study, Xi et al. [19] reported remarkable results in relation to junction temperature and thermal resistance determination of UV LEDs. This method is based on a comprehensive theoretical model for the dependence of diode-forward voltage on junction temperature. However, this method involves a crucial calibration measurement phase, requiring the use of a pulsed forward current with a very low duty cycle (0.1%). The emission-peak-shift method and the high-energy slope of the emission spectrum also the measurement of junction and carrier temperatures, respectively. Nevertheless, the accuracy of the measurement of the junction temperature of these two last methods ranges from ± 10 to $\pm 24\,^\circ$C, limited by the uncertainty of the peak position.

In 2004, Hong proposed a useful non-invasive method based on the measurement of the peak wavelength shift of AlGaInP LEDs versus temperature (ranging from 25 to 70 °C) and drive current using a spectroradiometer of ± 2 nm spectral accuracy. The junction temperature was calculated considering both the measurement of forward voltages at two known ambient temperatures and the temperature coefficient of the forward voltage, assuming a linear relationship between voltage and temperature [20]. The main difficulties with this approach could be related to the extraction of the nominal peak wavelength with high