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Influence of cooling rate on alternating current light-emitting diode with multiple quantum wells

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ABSTRACT

Influence of cooling rate on ac LED (light-emitting diode) with multiple quantum wells is investigated in the present study. A semi-empirical model based on existing experimental measurements is proposed to describe the relationship between the current density and the forwards voltage drop across the *p*–*n* junction for LEDs with multiple quantum wells. The numerical model then is employed to compute the electrical and temperature fields on ac LED with multiple quantum wells under various cooling rate. The resulting temperature of the LED oscillates under ac current. The temperature increases due to the heat generated in the active layer of the LED when the electrical potential exceeds the threshold voltage. Otherwise, there is no electrical current and thus the temperature decreases due to the effect of the cooling device. Both light-emitting power and maximum temperature increase as expected when the applied ac electrical potential increases. Fortunately, the temperature of the LED can be efficiently controlled by increasing the cooling rate of the cooling device. Although increasing the cooling rate would decrease the light-emitting power, the influence is not significant.

1. Introduction

The light-emitting diodes (LEDs) have recently been commercialized in general lighting, architecture decoration, and backlight modules. Compared to traditional light sources, LEDs have some major advantages such as longer lifetime, narrow spectrum, good mechanical stability, high color rendering index, and most importantly high energy efficiency [1–3]. However, the high current density occurring in high-power LEDs produces high temperature in the *p*–*n* junction of the LEDs that creates the droop effect [1,4,5]. The droop effect causes great degrade in the device performance.

The relationship between the current density J and the forward voltage drop V_f across the *p*–*n* junction in a diode is known as JV curve [6,7]. The JV curve for conventional LEDs without quantum wells is described by

$$J = J_s\left(\exp\left(\frac{eV_f}{nk(T+273)}\right) - 1\right) \tag{1}$$

where J_s is the saturation current density, e is the elementary charge, k is the Boltzmann constant, and T is the temperature (in Celsius) at the *p*–*n* junction. This is the well-known Shockley equation if the ideality factor n is dropped from Eq. (1). The Shockley equation was derived by Shockley [8] under the assumption of no carrier recombination in the *p*–*n* junction zone in 1949. Sah et al. [9] subsequently modified the equation by adding the ideality factor n to Eq. (1) with $1 < n \leqslant 2$ to take the effect of carrier recombination into account. The modified Shockley equation is often extended to LEDs with quantum wells [10–14]. The most popular approach is to use the modified Shockley equation with a value of n that best-fits the measured JV curve [7].

Lee and coworkers [6,7,15] pointed out that the modified Shockley equation does not apply to LEDs with quantum wells for the following reasons. For LEDs without quantum wells, the current arising from the carrier recombination is significant only when the forward bias voltage is small. However, LEDs are forward-biased heavily in typical operation. Under this condition, the carrier recombination current can be entirely ignored. By contrast, for LEDs with quantum wells holes and electrons are injected into the quantum wells where one electron recombines with a hole and releases a photon that significantly improves the light-emitting power of the LED. This implies that the current in LEDs with quantum wells is essentially the recombination current. The modified Shockley equation [9] formulates almost only the diffusion current, and thus inappropriate for LEDs with quantum wells. More discussion on the correctness of the Shockley equation can be found in [16,17].

Current crowding effect was another problem encountered in the development of the LEDs. In the absence of transparent contact layer, most light generated in the *p*–*n* junction of the LED would be

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absorbed by the opaque electrodes. To improve the current spreading (and thus better light extraction and more uniform heat generation), a few methods including the use of indium tin oxide (ITO) layer [18–21], *p*-type transparent electrodes [13,22,23], and particularly-patterned electrodes [24–26] have been developed. However, most of the previous works on the modeling of the LEDs have mainly concentrated on the current transport and light extraction. The thermal effects, including the heat generation in the *p*–*n* junction and the heat energy extracted by the cooling device, have attained less attention. Estimation of the conversion efficiency [27] is one of the major difficulties in the thermal modeling of LEDs. Conversion efficiency is the ratio of the light-emitting power to the electrical power consumption when the current goes across the active layer of the LEDs. It accounts for the competition between the radiative and non-radiative recombination channels [28] as well as the possible carrier leakage from the *p*–*n* junction zone. Bulashevich and coworkers [29–32] and Chen and coworkers [2,33,34] seem to be the only two research groups (accessible in the public literature) who have modeled the electrical and thermal coupling problem for LEDs.

Bulashevich and coworkers [30] introduced a one-dimensional drift–diffusion approach for the electron and hole transports in the *p*–*n* junction zone. The radiative recombination rate was integrated over the *p*–*n* junction zone to yield the internal quantum efficiency (similar to the conversion efficiency). However, the value of the radiative recombination rate was not defined in Ref. [30]. In their study, Chen and coworkers determined the conversion efficiency experimentally [34]. The measured conversion efficiency is roughly 0.25 in the operation range of the LED, although the conversion efficiency would slightly decrease as the temperature increases. The modified Shockley equation with ideality factor of 2.25 and 1.54 was employed. Both research groups of Bulashevich's and Chen's considered only one cooling device (or one given cooling rate). Influence of the cooling rate provided by the cooling device was not investigated. In the present study, a semi-empirical model based on existing experiments is demonstrated to evaluate the forwards voltage drop under given current density and temperature for a LED with multiple quantum wells. The numerical model then is employed to investigate the influence of the cooling rate on a LED with multiple quantum wells under alternating current.

2. Theoretical analysis

To investigate the characteristics of the JV curve for LEDs with multiple quantum wells, Lee et al. [7] fabricated a LED with multiple quantum wells, and then measured the JV curve for this particular LED. The temperature at the *p*–*n* junction of the LED estimated from the measured thermal resistance (166 K/W) between the *p*–*n* junction and the case was

$$T = 166 J V_f + 27 \tag{2}$$

where T is in Celsius. For convenience, their measured JV curve (the effect of the series resistance has been extracted) is plotted in Fig. 1. The seven black dots on the JV curve denote the temperature at $T = 30\,^\circ\mathrm{C}, 40\,^\circ\mathrm{C}, \ldots, 90\,^\circ\mathrm{C}$ according to Eq. (2). Due to the lack of more reliable experimental data, the derivative of the junction voltage with respect to the junction temperature (known as K-factor) for a GaN ultraviolet LED

$$\frac{\partial V_f(T,J)}{\partial T} = -0.0023\ \mathrm{V/K} \tag{3}$$

from Xi and Schubert [35] is assumed valid for the present LED with multiple quantum wells. This leads to a system of temperature-dependent JV curves as shown in Fig. 1.

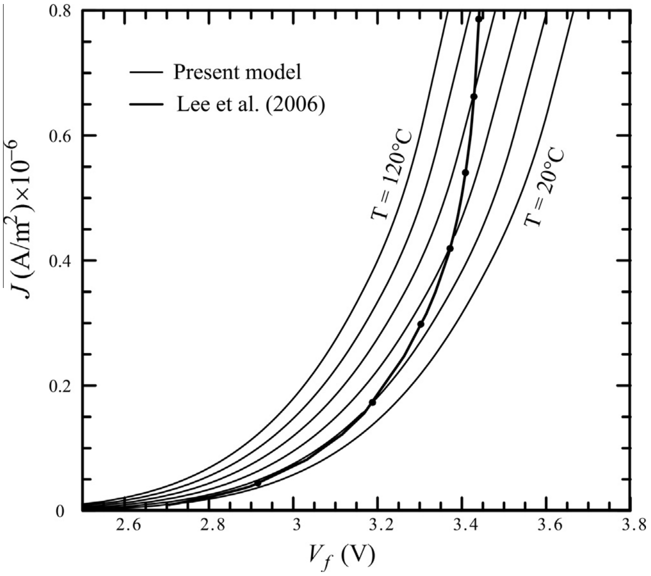

Fig. 1. The proposed temperature-dependent JV curves for the LED [7] based on the K-factor from Xi and Schubert [35].

Upon introducing the dimensionless transformation

$$\xi = 25\left(\frac{V_f}{V_{f0}} - 1\right), \quad j = \frac{J}{J_0} \tag{4}$$

the JV curves in Fig. 1 essentially merge into a single function (Bernoulli function) in the low current density limit

$$j = B(\xi) = \frac{\xi}{1 - \exp(-\xi)} \tag{5}$$

while become linear functions in the high current density limit

$$j = a\xi \tag{6}$$

where

$$V_{f0} = 3.443 + (13.2T^2 - 4440T) \times 10^{-6}\ \mathrm{V}$$

$$J_0 = 10.53T^2 - 1458T + 296{,}600\ \mathrm{A/m^2} \tag{7}$$

$$a = (3.983T^2 - 406.3T + 111{,}200)\frac{V_{f0}}{J_0} \tag{8}$$

In the formulation, a is dimensionless while T is in Celsius. To achieve a smooth transition between the Bernoulli function (5) and the linear function (6), the JV curve at a constant temperature is approximated with a Hermite polynomial by letting ξ be a cubic polynomial of j in the interval $\gamma_1 \leqslant j \leqslant \gamma_2$, where $\gamma_1 = j_b - 0.48$, $\gamma_2 = j_b + 0.48, j_b = a\xi_0$ with $\xi_0 = \ln\left(\frac{a}{a-1}\right)$ being the intersection point of the Bernoulli function (5) and the linear function (6).

Fig. 2 shows a schematic diagram of typical LEDs with multiple quantum wells. The LED analyzed in the present study is a square chip of dimension $L = 1000\ \mu\mathrm{m}$. The multiple quantum wells are located inside the active layer. The electrical conductivities of *n*-GaN, *p*-GaN, ITO, and the thermophysical properties of *n*-GaN from the literature [2,18–21,33,36–39] and that employed in the present study are listed in Table 1. Use of the ITO layer is to achieve a good current spreading as mentioned earlier. It is important to note that the electrical conductivity of the *p*-GaN layer is very small as compared to that of the *n*-GaN layer and the ITO layer. Moreover, there is a great electrical potential drop across the active layer. Hence, the electrical current would spread along the ITO layer, and then goes through the *p*-GaN layer and active layer perpendicularly on