The nonlinear thermal model of heterojunction light emitting diodes

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Abstract. Feature of heterojunction light-emitting diodes (LEDs) is that their internal quantum efficiency decreases with the growth of temperature and current density, which leads to additional positive electrothermal feedback. For an estimation of these effects nonlinear electrothermal model of power LED with dependences internal quantum efficiency from temperature and current density and dependence of factor of heat conductivity of a substrate on temperature is offered. It is shown, that action of these electrothermal feedback mechanisms leads to increase in heterogeneity of distribution of temperature and current in structures of LED in comparison with linear model and to nonlinear increase in thermal resistance of LEDs with current growth. Results of measurement of the thermal impedance of serial power LEDs is well described by the offered model.

1. Introduction

It is known, that intensity of radiation and durability heterojunction light emitting diodes (LED) decrease with the increase in the temperature of an overheat of heterojunction [1]. Analysis of thermal properties LED usually assumes, that the power density is uniformly distributed on the heterojunction area [1,2]. However even at uniform distribution of sources of heat on surface of structures as a result of non-uniform heat removal from its various parts distribution of temperature will be non-uniform. Exponential dependence of density of a current on temperature as a result of positive electrothermal feedback (PETF) leads to increase of this non-uniformity, and with increase in a total current the non-uniformity of distribution of density of a current and temperature increases.

The feature of heterojunction LED is that their internal quantum efficiency decreases with the growth of temperature and current density, which leads to additional PETF: full electrical power, transformed to heat, and density of heating power in more warm areas of heterojunction will increase, which leads to stronger increase of heterogeneity.

2. The nonlinear electrothermal model of light emitting diodes

For calculation and the analysis of the specified effects has been considered electrothermal model InGaN/GaN heterojunction structure on the sapphire substrate placed on metal heat-tap (figure 1). As the thickness and depth of placing heterojunction are small, heat sources in this model were considered surface-distributed.
The mathematical model describing thermal properties of considered structure LED, includes system from the stationary equation a heat conductivity and the thermogeneration equations, under adiabatic conditions on lateral borders. Dependence of density of current LED from temperature is defined its I-V characteristic:

$$J(x,y) = C \cdot \exp \left( - \frac{E_g - e(U_D - \rho_a L_{get} I_{T_a}(y))}{p k T_a(x,y)} \right),$$

(1)

where $C$ – parameter weakly depending on temperature, $U_D$ – direct voltage on LED, $E_g$ – band energy of the semiconductor, $T_a(x,y)$ – temperature in a heterojunction plane, $\rho_a$, $L_{get}$ – specific resistance and a thickness of heterostructure accordingly, $k$ – Boltzmann’s constant, $e$ – an electron charge, $p$ – the parameter, depending on the mechanism of current carrying in heterostructure, $x$, $y$ – coordinates on a surface of heterostructure. The density of electric power, transforming in heat on surface of substrates, is defined by the formula

$$q(x,y) = \left[ 1 - \eta(T_a, J) \right] J(T_a) U_D,$$

(2)

where $\eta$ – the internal quantum efficiency of heterostructure which are function of temperature and density of a current. At the set total current through LED for a finding of value $U_D$ it necessary to known distribution of temperature to solve the such equation

$$\int_{S_{sr}} J(U_D, T_a) dx dy = I_D,$$

(3)

where $S_{sr}$ – the area of active area of structure.

Dependences $\eta$ from temperature and current density it was described by such function:

$$\eta(T,J) = \eta_0(T_J, J_0) \exp \left( - B\Delta T - D\Delta J \right),$$

where $\Delta T$ and $\Delta J$ – deviations of temperature and density of a current from initial values $T_0$ and $J_0$, $\eta_0(T_J, J_0)$ – value of quantum efficiency at $T_0$ and $J_0$; values of parameters $B$, $D$ and $\eta_0$ were defined according to [1]. From settlement temperature distributions (figure 2) at different combinations of parameters it is visible that dependence of quantum efficiency on current and temperature density leads to increase in the maximum overheating of structure in 1.2-1.3 times in comparison with linear model $\eta = \text{const}$ [3].
Heterogeneity of temperature leads to non-uniform distribution of density of a current for which description use [4] linear approach $J = J_0 + \xi_1 (T_n^0 - T_n)/T_0$, where $\xi_1$ temperature factor of density of a current under condition of (3). Measuring thermal parameter LED is thermal resistance junction-case, which in one-dimensional model is defined by expression

$$R_{J_{f-c}} = d/S_{at} \lambda_n,$$

where $d$ – a thickness of a substrate, $S_{at}$ – the area of active area of a LED, $\lambda_n$ – factor of heat conductivity of a substrate material. For more adequate definition of thermal resistance at non-uniform current distribution in expression (4) it is necessary to use the effective area of active area, which is defined as the relation of average density of a current to maximum: $S_{eff} = S_{at} \left[1 + \xi_2 (T_n^max - T_n)/T_0\right]$. As a result of action of considered mechanisms PETF the effective area of LED will decrease, and thermal resistance junction-case of LED increase with full current growth. In linear approach this dependence can be described by the expression $R_{J_{f-c}} \approx R_{J_{f-c}0} (1 + \xi_1 I_D)$. By our estimations $\xi_1 \approx (0.3\pm0.4)I_{max}^{-1}$, where $I_{max}$ – the maximum working current LED.

Other fundamental reason leading to dependence of thermal resistance from a total current is dependence of factor of heat conductivity of a substrate on temperature. If accept as modeling approximation of this dependence expression $\lambda = \lambda_n(T_n/T)$ in linear approach this dependence can be described as the expression $R_{J_{f-c}} \approx R_{J_{f-c}0} (1 + \xi_2 I_D)$. Contribution of this mechanism to the general steepness current dependences is less compared with mechanisms non-uniform current distribution ($\xi_1 > \xi_2$); at the increase in a current from 0 to maximum value thermal resistance to increase by 20-30%.

3. Experimental results

For measurement of parameters of nonlinear thermal models LED the experimental sample is offered of a microcontroller measuring instrument of a thermal impedance of diodes [5]. Results of measurement of frequency dependences of the module of thermal impedance $Z_f(\omega)$ serial high power LED XRC-RED-L1-R2-M2-C-1 ($I_{max} =350$ mA), produced by firms Cree, are shown on figure 3.
Figure 3. Dependence of the module of a thermal impedance high power LED from frequency of modulation of heating power in an air at a current 350 mA: continuous line – experiment; shaped line – theory.

Values of the module of a thermal impedance are measured on the bottom shelf (\(\omega \approx 1500\) rad/s) correspond to junction-case thermal resistance. With increase in a heating current from 200 mA to 550 mA thermal resistance of a substrate increases in 1.6-1.7 times (figure 4) that is well described within the limits of the offered model.

Figure 4. Dependences of junction-case thermal resistance of two high power LEDs from total current.

4. Conclusion
It is shown, that dependence of quantum efficiency on temperature and current density leads to increase in heterogeneity of distribution of temperature and current in structures of power light-emitting diodes in comparison with linear model. As a result of action of this electrothermal feedback mechanism also dependence of the factor of heat conductivity of substrate from temperature effective thermal resistance of LEDs nonlinear increase with current growth.

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