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Thermal measurements and analysis of AlGaInP/GaInP MQW red LEDs with different chip sizes and substrate thicknesses

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ABSTRACT

Thermal properties of AlGaInP/GaInP MQW red LEDs are investigated by thermal measurements and analysis for different chip sizes and substrate thicknesses. To extract the thermal resistance (R_{th}), junction temperature (T_j) is experimentally determined by both forward voltage and electroluminescence (EL) emission peak shift methods. For theoretical thermal analysis, thermal parameters are calculated in simulation using measured heat source densities. The T_j value increases with increasing the injection current, and it decreases as the chip size becomes larger. The use of a thin substrate improves the heat removal capability. At 450 mA, the T_j values of 315 K and 342 K are measured for $500 \times 500\ \mu m^2$ LEDs with 110 μm and 350 μm thick substrates, respectively. For $500 \times 500\ \mu m^2$ LEDs with 110 μm thick substrate, the R_{th} values of 13.99 K/W and 14.89 K/W are obtained experimentally by the forward voltage and EL emission peak shift methods, respectively. The theoretically calculated value is 13.44 K/W, indicating a good agreement with the experimental results.

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1. Introduction

AlGaInP-based light emitting diodes (LEDs), which cover a broad wavelength spectrum from yellow green to red, have been widely used as a light source for various applications of displays, traffic signals, signs, and general lightings [1–3]. Recently, the progress in material growth, LED structure, and chip processing technology including window/current spreading layers, reflectors, electrode design, and surface roughening has significantly improved the device performance [4–8]. Nevertheless, further efforts towards the realization of high-power AlGaInP-based LEDs are still required for many practical applications. To achieve high output power, the LEDs should operate under high injection current. However, high electrical power increases the junction temperature (T_j) of LEDs due to the enhanced internal device heating. The temperature rise in the junction is the primary cause to degrade the optical output power, reliability, and lifetime of LEDs. Thus, the T_j is a key factor in analyzing the thermal performance of LEDs and it should be measured effectively for a variety of different structures.

The T_j can be experimentally measured by using the forward voltage method, micro-Raman spectroscopy, electroluminescence (EL), and photoluminescence [9–13]. The internal temperature change of LEDs with injection current, which is caused by the self heating effect, can be accurately predicted. Furthermore, thermal simulation makes it possible to get a better understanding of the thermal behaviors of LEDs. Although many studies have investigated the thermal characteristics of GaN-based blue LEDs, there were relatively few reports on the detailed thermal analysis of red LEDs based on AlGaInP materials. Furthermore, the investigation on the thermal analysis of AlGaInP LEDs with vertical electrodes is very useful for vertical LED structures. In this paper, we studied systematically the thermal characteristics of AlGaInP/GaInP multiple quantum well (MQW) red LEDs with different chip sizes for 110 μm and 350 μm thick substrates. Thermal resistance (R_{th}) as well as junction temperature was experimentally and theoretically investigated.

2. Device structure and thermal modelling

Fig. 1 shows the schematic diagram of AlGaInP/GaInP MQW red LEDs with vertical electrodes employed in this experiment. The AlGaInP/GaInP LED structure was grown on a 350 μm thick n-GaAs substrate by using metal organic chemical vapour deposition. After growth of a 0.2 μm thick n-GaAs buffer layer, a 1.2 μm thick n-AlAs/AlGaAs distributed Bragg reflector (DBR) was grown. The 0.7 μm thick 20 pairs of u-AlGaInP/GaInP MQWs were embedded between a 1 μm thick n-$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer and a p-type cladding layer. The p-type cladding layer was composed of a 0.7 μm thick AlInP layer and a 0.323 μm thick p-$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer, followed by a 0.03 μm thick AlGaInP tensile strain barrier reducing (TSBR) layer, and then it was completed by a 9 μm thick

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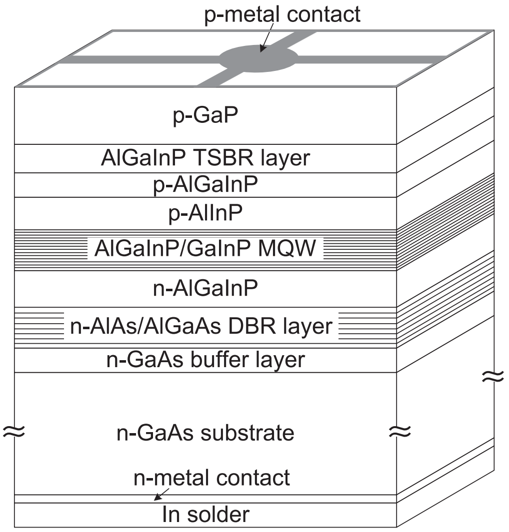

Fig. 1. Schematic diagram of AlGaInP/GaInP MQW red LEDs with vertical electrodes employed in this experiment.

p-GaP window layer. The wafers were processed into LEDs with different chip sizes of $300 \times 300\ \mu m^2$, $400 \times 400\ \mu m^2$, and $500 \times 500\ \mu m^2$. The mesa structures were formed by using inductively coupled plasma (ICP) etcher in $SiCl_4$/Ar plasma. After that, the p electrode of Au/AuBe was deposited on p side by using e-beam evaporator. For some devices, the n-GaAs substrate was lapped and polished up to the thickness of $\sim 110\ \mu m$. Then, the n electrode of AuGe/Ni/Au was formed on n side. Finally, the devices were annealed by using rapid thermal annealing in an N_2 ambient at 500 °C for 1 min to form ohmic contacts. For characterization, the fabricated LEDs were bonded on copper heatsink using indium solder and they were wire-bonded to an external contact pad with gold (Au) wire to inject the current. The prepared samples were characterized at various heatsink temperatures. Depending on the monitored temperature by a thermistor located in close proximity to the device, the temperature of LEDs was controlled on the thermoelectric cooler stage.

Thermal analysis of LEDs was carried out theoretically by finite element method (FEM) simulation using a steady-state 3D heat dissipation model. From measured heat source densities, the thermal parameters, such as junction temperature, temperature distribution, heat flux, and thermal resistance, were theoretically simulated for different chip sizes and substrate thicknesses. To simplify the simulation model, the uniform heat generation was assumed within the active region. The generated heat is transferred by three heat transfer mechanisms, i.e., conduction, convection, and radiation. The steady-state ($\partial/\partial t = 0$) 3D heat conduction equation is represented by [14]:

$$-k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right] = Q, \tag{1}$$

where k is the thermal conductivity of the constituent materials, Q is the heat source density, and T is the temperature. The heat is partly transferred through the device surfaces in the air by convection and radiation. But the radiation heat transfer can be neglected because it is not primary heat transfer mechanism in this simulation. At boundaries between device surfaces and air, the convection heat transfer can be calculated by the following equation [14]:

$$k\left[\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}+\frac{\partial T}{\partial z}\right] = h(T_{\text{inf}} - T), \tag{2}$$

Table 1
Thermal conductivities of the constituent materials for AlGaInP/GaInP MQW red LEDs at 298 K [18–20].

Name	Material	Thermal conductivity (W/m K)	Thickness (μm)
p-Electrode	Au/AuBe	315	0.5/0.15
p-Window layer	GaP	77	9
TSBR layer	AlGaInP	177	0.03
p-Cladding layer	$(Al_{0.3}Ga_{0.7})_{0.5}InP$/ $(Al_{0.7}Ga_{0.3})_{0.5}InP$	8.2/5.6	0.023/0.3
	AlInP	76.2	0.7
Active layer (20 pair)	GaInP/AlGaInP MQW	$k_L = 10.2$, $k_V = 8.6$	0.7
n-Cladding layer	$(Al_{0.7}Ga_{0.3})_{0.5}InP$/ $(Al_{0.5}Ga_{0.5})_{0.5}InP$	5.6/6.6	0.5/0.5
n-DBR	AlAs/AlGaAs	$k_L = 53.6$, $k_V = 20.3$	1.2
n-Buffer layer	GaAs	44	0.2
n-Substrate	GaAs	44	110 (350)
n-Electrode	AuGe/Ni/Au	315	0.12/0.03/0.3
Solder	In	81.6	3
Heatsink	Cu	400	–

where h is the convection heat transfer coefficient and T_{inf} is the ambient temperature.

The QWs and DBRs consist of multilayer thin-film structures. Compared to those of bulk materials, the thermal conductivities in QW and DBR structures should be modified due to the phonon confinement and interface effects [15,16]. For accurate thermal analysis, effective anisotropic thermal conductivities were considered in QW and DBR structures. The thermal conductivities of K_L in lateral direction and K_V in vertical direction are lower than those of bulk materials. Effective anisotropic thermal conductivity can be calculated by a formula related to the thickness and thermal conductivity of constituent materials [17]. Table 1 shows the thermal conductivities of the constituent materials for AlGaInP/GaInP MQW red LEDs at 298 K. For all layers except for the QWs and DBRs, the isotropic thermal conductivities were used. Also, the thermal conductivity of electrodes was assumed as a value of Au.

3. Results and discussion

Fig. 2a shows the voltage–current–light (*V–I–L*) curves of LEDs with $300 \times 300\ \mu m^2$, $400 \times 400\ \mu m^2$ and $500 \times 500\ \mu m^2$ chip sizes for 110 μm thick substrate at 298 K under continuous-wave (CW) mode. For comparison, the *V–I* and *I–L* data of $500 \times 500\ \mu m^2$ LEDs with 350 μm thick substrate are also shown by dashed lines. As the injection current increased, the light output power of LEDs was linearly increased until its saturation began to occur. For larger chip size, the output power was increased distinctly at higher current level. At 480 mA, the output powers of 19.6 mW and 28.9 mW were obtained for $300 \times 300\ \mu m^2$ and $500 \times 500\ \mu m^2$ LEDs, respectively. The forward voltage was slightly decreased as the chip size became larger due to more surface states [21]. The turn-on voltage was also decreased from 1.81 V for $300 \times 300\ \mu m^2$ to 1.75 V for $500 \times 500\ \mu m^2$. For $500 \times 500\ \mu m^2$ chip size, the LED with a thin substrate of 110 μm emitted the higher output power under higher current as shown in Fig. 2a. At injection currents less than 240 mA, two LEDs show similar device characteristics. However, the output power was reduced above 240 mA for the LED with 350 μm thick substrate because of its enhanced internal device heating at higher current. At 480 mA, the output power was 25.1 mW for 350 μm thick substrate. The use of a thin substrate of 110 μm improved the output power by 15.1% compared to the 350 μm thick substrate.

Fig. 2b shows the CW *V–I–L* curves of the $500 \times 500\ \mu m^2$ LED with 110 μm thick substrate at various heatsink temperatures. The output power was 30.3 mW at 288 K and then it decreased

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