Numerical Investigation on the Negative Characteristic Temperature of InGaN Blue Laser Diodes

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Abstract

GaN-based blue laser diodes (LDs) can exhibit peculiar temperature characteristics such as quite a high characteristics temperature (T_0) or even negative T_0. The author investigates the temperature-dependent device characteristics of blue LDs having InGaN double quantum-well (QW) structures using numerical simulations. As the n-type doping concentration of a barrier layer between QWs increases, negative T_0 can be observed, which is found to originate from the increase of gain at the n-side QW with temperature as a result of the improvement of hole transport in QWs with temperature.

I. INTRODUCTION

GaN-based blue laser diodes (LDs) emitting in the wavelengths of 440 to 460 nm have attracted great attention for applications to the light source of the laser projection display, visible light communication, and laser-based white light sources [1-3]. The high output power and small etendue of GaN-based blue LDs should be advantageous to high brightness display, communication, and lighting applications. In addition, the blue LD-based white light sources can avoid 'efficiency droop' problem which has been commonly observed in GaN-based blue LEDs at high injection current.

In such display and lighting applications of blue LDs, temperature-stable operations are highly desirable. Temperature dependence of LDs is usually described by the following empirical expression:

$$I_{\mathrm{th}} = I_0 \exp(T/T_0), \qquad (1)$$

where I_{th} and T are threshold current and the absolute temperature, respectively. T_0 is the characteristic temperature, a phenomenological parameter that represents the temperature dependence of LDs.

Most of reported T_0 values in GaN-based LDs have ranged from 120 to 180 K. In some cases, however, abnormally high T_0 of >200 K or even negative T_0 values have been demonstrated [4-6]. Such unusual values of T_0 were attributed to either the temperature enhanced hole redistribution between quantum wells (QWs) or to the temperature dependence of the ballistic transport of electrons. However, the fundamental mechanism behind the value of T_0 was not clearly identified so far.

In this paper, in order to reveal the origin of the anomalous temperature characteristics in the InGaN blue LDs, we numerically investigate the temperature-dependence of light output versus injection current (*L-I*) curves in the blue LD structures emitting at 450 nm. In the simulations, we employ the laser technology integrated program (LASTIP), which has been widely used for the study of InGaN-based LD characteristics.

II. RESULTS AND DISCUSSION

LD layers used in this work were grown on a c-plane sapphire and the investigated LD structure is basically the same as that reported in Ref. [7]. The active region is assumed to consist of double InGaN quantum-well (QW) layers separated by a GaN barrier layer. The In composition and thickness of the InGaN QW is ~15% and 2.5 nm, respectively. The cavity length is 650 μm, and the reflectance on the front and the rear facet is 56% and 95%, respectively. In the carrier recombination model of LASTIP, the Schockley-Read-Hall recombination lifetime is assumed to be 50 ns and the radiative recombination rate is calculated by integrating the spontaneous emission spectrum. The Auger recombination coefficient is set at 2×10^{-31} cm^6/s which correspond to the recently reported Auger recombination coefficients of InGaN QWs.

In this study, the temperature dependence of *L-I* curves for different n-type doping concentration in the GaN barrier is compared. Figure 1(a) and (b) shows simulated *L-I* curves for temperatures from 20 to 100 °C when the doping concentration of the barrier layer is 1×10^{17} and 2×10^{18} cm^{-3}, respectively. Here, the barrier thickness is 15 nm. When the doping concentration is 1×10^{17} cm^{-3}, normal temperature dependence of *L-I* curves is observed. I_{th} increases steadily with temperature, resulting in T_0 of 180 K. For the doping concentration of 2×10^{18} cm^{-3}, however, the temperature dependence of *L-I* curves is quite abnormal. In this case, I_{th} decreases as temperature increases from 20 to 100 °C, resulting in T_0 of -200 K. This result indicate that the temperature dependence of I_{th} is strongly influenced by the doping concentration of the barrier layer in MQWs.

In order to understand the results, carrier concentration and gain distribution in QWs were calculated. It was found that the hole distribution becomes inhomogeneous as the n-doping concentration of the barrier increases. Consequently, gain of the n-side QW decreases as the doping concentration increases. Figure 2 shows the gain at two QWs for temperatures 20, 60, and 100 °C when the doping concentration is (a) 1×10^{17} and (b) 2×10^{18} cm^{-3}.

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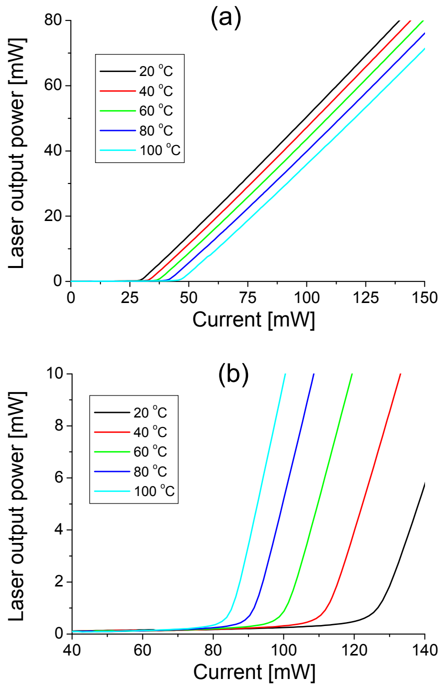

Fig. 1. *L-I* curves of InGaN blue laser diodes as temperature varies from 20 to 100 ºC when the doping concentration of the GaN barrier layer is (a) 1×10^{17} and (b) 2×10^{18} cm^{-3}.

For both cases, gain at the p-side QW is larger than that at the n-side QW that is related to the hole transport from the p-GaN to the active region. For the doping concentration of 1×10^{17} cm^{-3}, gain at the n-side QW is still positive and it does not change much with temperatures. For the doping concentration of 2×10^{18} cm^{-3}, however, gain at the n-side QW is negative, which means that the n-side QW absorbs light resulting in the increase of threshold. As the temperature increases, hole transport becomes improved and the carrier density at the n-side QW increases. Therefore, gain at the n-side QW increases as the temperature increases, which contribute to the decrease in T_0 with increasing temperature. That is, the simulation result shows that the negative T_0 of InGaN blue LDs is basically attributed to the poor hole injection efficiency from the p-GaN to MQW layers.

III. CONCLUSIONS

In this work, temperature-dependence of *L-I* curves in InGaN double QW blue LDs was numerically investigated using LASTIP simulation. The I_{th} and T_0 were found to depend strongly on the n-doping concentration in the GaN barrier layer between QWs. For the doping concentration of 1×10^{17} cm^{-3}, normal temperature dependence with T_0 of 180 K was obtained. For the doping concentration of 2×10^{18} cm^{-3}, however, negative T_0 of -200 K was obtained, which was attributed to the increase in the gain at the n-side QW with increasing temperature as a result of the improvement in hole injection efficiency.

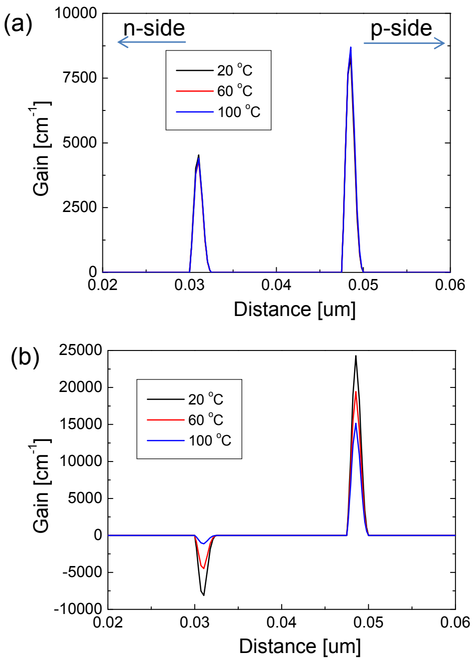

Fig. 2. Optical gain at two InGaN QWs for temperatures 20, 60, and 100 ºC when the doping concentration of the GaN barrier layer is (a) 1×10^{17} and (b) 2×10^{18} cm^{-3}.

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