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Extremely Stable Temperature Characteristics of 1550 nm Band *p*-Doped Highly Stacked Quantum-Dot Laser Diodes Grown on an InP(311)B Substrate

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Abstract

In this study, we fabricated 1.55 μm band *p*-doped 30 layers stacked quantum-dot laser diodes (QD-LDs) using a strain-compensation technique on an InP(311)B substrate, and we showed that the fabricated QD-LDs exhibit extremely stable temperature characteristics.

1. Introduction

With the exponential growth in Internet traffic in recent years, the development of ultra-fast and high-capacity photonic networks is urgently required. To establish such networks, an important characteristic for next-generation advanced optical devices is high temperature stability. In access networks, compact, low cost, and stable optical devices, such as laser diodes (LDs), photo diodes (PDs), and semiconductor optical amplifiers are necessary under various temperature conditions. In addition, for the application of datacenter or Datacom, high characteristics and stability are required for optical devices if they are integrated with large-scale integrated circuits. In contrast, quantum dots (QDs) are highly anticipated materials because of their ultra-fast response, low threshold, wide operation bandwidth, and high-thermal stability. Many groups have reported high-performance photonic devices by using QD structures [1]. So far, high characteristic temperature (T_0) of more than 227 K [2] around room temperature has hardly been reported at a 1.5 μm band, even though extremely high T_0, such as 320 K [3] and almost infinity (around room temperature) [4-5], has been reported at a 1.3 μm band. In this paper, we fabricated 1.55 μm band *p*-doped 30 layers stacked QD-LDs by using a strain compensation technique [6] on an InP(311)B substrate, and showed that the fabricated QD-LD has extremely stable temperature characteristics.

2. Device Structure

Fig. 1 (a) shows the schematic of the fabricated QD epitaxial wafer. The fabricated QD wafer consists of 150 nm *n*-InAlAs cladding layer, 30 pairs of InGaAlAs spacer and InAs QD layers, 2 μm *p*-InAlAs cladding layers, and 100 nm p^+-InGaAs contact layers grown on an InP(311)B substrate by using molecular beam epitaxy. A *p*-dopant of 1×10^{18} cm^{-3} was doped in the InGaAlAs spacer layers by using a modulation doping method. Fig. 2 shows an atomic force microscope (AFM) image of the fabricated QD structure. The QD sheet density is estimated to be 9.2–9.6 × 10^{10} cm^{-2}. Moreover, we fabricated QD-LDs with a broad area structure through conventional photolithography. The width of the cavity was 50 μm, and its length was 600–1400 μm with as-cleaved facets.

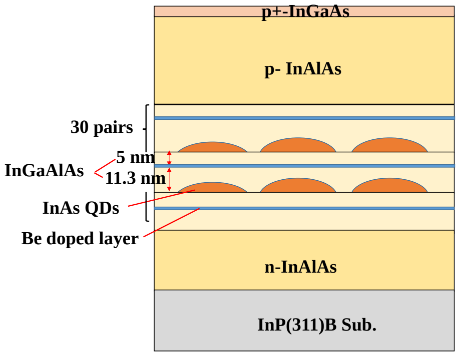

Fig.1 Schematic of the *p*-doped QD epitaxial wafer formation using strain compensation technique.

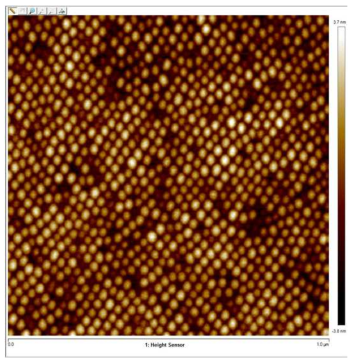

Fig.2 AFM image of fabricated QD structure (1 μm × 1 μm).

3. Results and Discussions

Figs. 3 (a) and (b) indicate the optical output power characteristics of *p*-doped and nondoped LDs at 15–80 °C with driving pulse current of 1 μs width and 1% duty cycle. The threshold currents of *p*-doped and nondoped LDs were 1710 and 567 mA respectively at 25 °C. In this measurement, the lasing peak wavelengths of *p*-doped and nondoped QD-LDs at room temperature were 1555 and 1526 nm, respectively.

Fig. 4 shows the characteristics of threshold current densities dependent on temperature in each sample. For verification of the *p*-doped QD-LDs, we fabricated two other *p*-doped QD wafers, in which the epitaxial profile was the same. As shown in Fig. 4, extremely high T_0 values of 1691 and 5942 K were obtained at room temperature in *p*-doped QD-LDs, whereas T_0 of nondoped QD-LDs was 118 K. This indicates that our fabricated 1.55 μm-band QD-LD has extremely stable temperature characteristics. Furthermore, in one of the two *p*-doped samples, a negative value of characteristic temperature T_0 was obtained at lower a value of room temperature. This may be the unique phenomenon, which has been reported at extremely low temperatures [7].

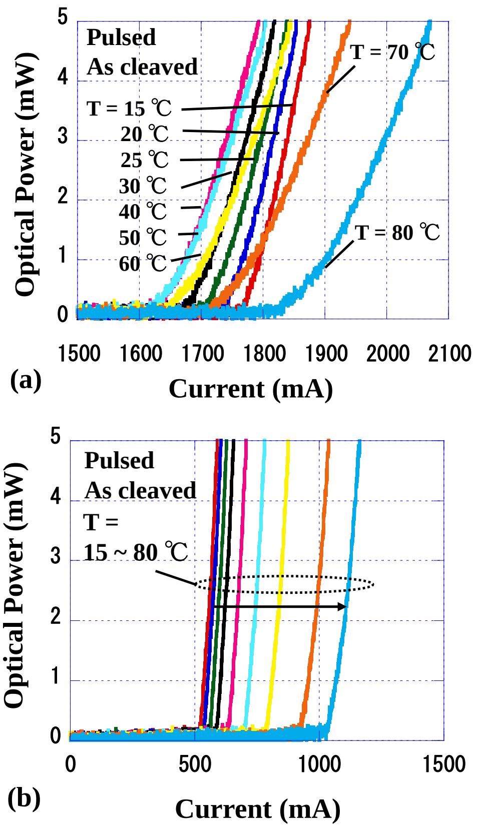

Fig.3 Optical output power characteristics of (a) *p*-doped and (b) nondoped QD-LDs at 15–80 °C.

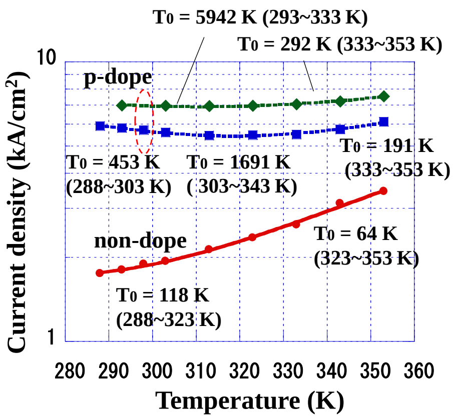

Fig.4 Characteristics of threshold current densities dependent on temperature in each sample.

Fig. 5 shows the relationship between the reciprocal of external quantum efficiency η_d and cavity length. From this result, we estimated the internal quantum efficiencies η_i of *p*-doped and nondoped QD-LDs to be 15% and 47% respectively, and internal optical losses to be 17.4 and 15.3 cm^{-1}, respectively.

The internal quantum efficiency of *p*-doped LD was lower than that of nondoped LD because the relatively high concentration of doped acceptor decreased the internal quantum efficiency and increased the effect of free carrier absorption. Therefore, as shown in Fig. 3, the threshold current of *p*-doped LD is three times higher than that of the nondoped LD because the internal efficiency of *p*-doped LD is reduced to one-third. In this experiment, although the threshold current or current density were relatively high because the structure of QD-LDs was not optimized, it is expected that the 1.55 μm band *p*-doped highly-stacked QD-LD grown on an InP(311)B substrate has the potential to have a threshold current of approximately 20–30 mA if a ridge structure and facet coating are used and active layer volume is optimized.

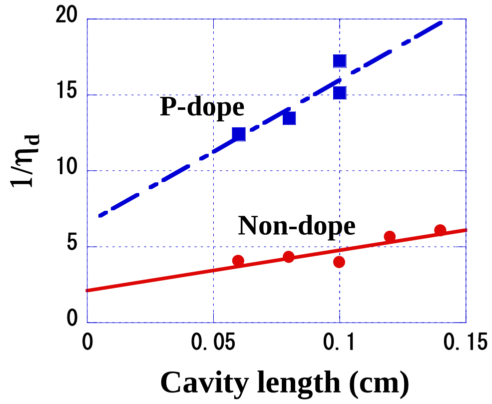

Fig.5 Relationship between the reciprocal of external quantum efficiency η_d and cavity length.

4. Conclusions

We fabricated 1.55 μm band *p*-doped 30 layers stacked QD-LDs by using a strain compensation technique on an InP(311)B substrate, and showed that the fabricated QD-LDs have extremely stable temperature characteristics.

Acknowledgements

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