Current-injection T-shaped quantum wire lasers with perpendicular doping layers operating at 100K

Makoto Okano a,1, Shu-man Liu a, Masahiro Yoshita a,b, Hidefumi Akiyama a,b, Loren N. Pfeiffer b and Ken W. West b

a Institute for Solid State Physics, University of Tokyo, and CREST, JST, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan
b Bell Laboratories, Alcatel Lucent, 600 Mountain Avenue, Murray Hill, New Jersey 07974 USA

Abstract

We demonstrated lasing from current-injection T-shaped GaAs/AlGaAs quantum wire (T-wire) lasers with perpendicular p- and n-doping layers. The T-wire laser showed lasing between 5 and 110 K, and showed the optimal threshold current of 2.1 mA and differential quantum efficiency of 0.9% at 100 K. In microscopic-EL imaging measurements, we observed the emissions from the outside of optical core region, which indicated overflow of holes from the active region.

Key words: Quantum wire, Laser diode, Carrier injection, µ-EL imaging
PACS: 78.20.Ci, 78.60.Fi, 78.67.Lt

1. Introduction

Cleaved-edge-overgrowth (CEO) T-shaped quantum-wire (T-wire) lasers have significant advantages such as high controllability, high uniformity, and high crystal quality, and are appropriate for verifying expected advanced performances of one-dimensional quantum-wire lasers [1]. The first current-injection T-wire lasers, consisting of 15-arrayed 7 nm × 7 nm T wires and having a unique carrier-injection scheme where the carriers were injected via two perpendicular intersecting quantum wells modulation-doped in p- and n-types, were fabricated in 1994, and showed multi-mode lasing of threshold currents of 0.4–0.8 mA at 4.2 K [2]. Since this first demonstration, however, no quantitative laser characteristics such as output power, quantum efficiency, and their temperature dependence have been reported.

In this work, we achieved cw single-mode lasing between 5 and 110 K in the T-wire laser with improved T-wire structures for higher-temperature operation. The laser showed a low threshold current of 2.1 mA and

---

1 Corresponding author. E-mail: m-okano@issp.u-tokyo.ac.jp

---

Fig. 1. A schematic view of a current-injection T-wire laser with perpendicular doping layers. Percentages represent content x of Al. The black arrows and white arrow indicate the injecting paths of electrons and holes, respectively.
a high differential quantum efficiency of 0.9% at 100 K. We also observed temperature and bias-current dependence of near-field emission patterns of the T-wire laser from a cavity edge. In these measurements, the emission from outside of active region was observed at whole the operating temperatures, which indicates that the injected holes overflowed from the active region.

2. Material and device performance

Figure 1 shows the schematic view of the current-injection T-wire laser with perpendicular p- and n-doping layers fabricated by the CEO method with molecular beam epitaxy and a growth-interrupt annealing technique [3]. The T wires are formed at T-intersections of 15-period 14 nm (001) Al0.07Ga0.93As multiple quantum wells (denoted as stem wells) and a 6 nm (110) GaAs quantum well (denoted as arm well). The T wires were embedded in the core of the optical waveguide surrounded by Al0.5Ga0.5As digital-alloy cladding layers. Laser bars of a cavity length of 500 µm were formed by cleavage after making metal electrodes. The cavity facets were covered with thin Au films for high reflection. Details of sample structures and fabrication processes are described elsewhere [4].

Bias-current dependence of electroluminescence (EL) spectra from a cavity edge of the T-wire laser at 100 K is shown in Fig. 2(a). Emission peaks at 1.543 and 1.562 eV on the spectrum at the low bias current (Ib) of 0.25 mA were assigned, by microscopic-EL (µ-EL) imaging measurements, to the T wires and the arm well on the Al0.3Ga0.7As cap layer (denoted as cap-arm-well), respectively. As the bias current was increased, the emission from the T wire became dominant, and ended up a single-mode lasing above the threshold current (Ith=2.1 mA). Figure 2(b) shows the lasing spectra above threshold currents for various temperatures. The sample showed single-mode lasing from 5 to 110 K while it stopped lasing above 120 K. This limit of operating temperature is higher than those in other current-injection T-wire lasers ever reported [2,5]. Red-shift of the lasing energy with increasing temperature is consistent with the temperature dependence of band-gap energy of GaAs.

The temperature dependence of threshold current and differential quantum efficiency (ηd) derived from the output power versus bias current characteristics, is shown in Fig. 3. The Ith and ηd were improved with increasing temperature and became optimal at 100 K, but they were degraded at 110 K.

3. µ-EL imaging measurement

To understand current-injection mechanisms in the T-wire lasers, we observed spectrally resolved µ-EL images from a cavity edge for various temperatures. The spatial resolution of the imaging system using a microscope objective lens (numerical aperture = 0.5) was 1 µm.

Figure 4 shows bias-current and temperature dependence of near-field patterns of emissions from a cavity edge of the T-wire laser. In the images, outlines of the T-waveguide are superimposed. The crosshatched regions correspond to the cladding layers. The fundamental optical mode calculated by a finite element method is shown in Fig. 4(a). Black contour curves represent probabilities (|ψ|^2| = 0.3, 0.6, 0.9) of photons.

Figure 4(b) shows the emission patterns at 100 K for various bias-currents observed at the centre energy (Ecm) of 1.545eV selected by an interference bandpass filter (Δλ = 2 nm). This energy corresponds to the emis-

---

(a)

(b)

Fig. 2. (a) Electroluminescence spectra of the T-wire laser from a cavity edge for various bias currents at 100 K. (b) Temperature dependence of lasing spectra above threshold currents.

Fig. 3. The temperature dependence of threshold current and differential quantum efficiency. They are optimal at 100K.
Fig. 4. (a) Calculated optical mode of the T-waveguide. (b) Emission patterns of the T-wire laser from a cavity edge observed at the energies ($E_{det}$) selected by a bandpass filter for three bias currents at 100 K. (c) Emission patterns observed at $E_{det}$ for three temperatures. In all images, outlines of the T-waveguide are superimposed and the crosshatched regions represent optical cladding layers.

Next, we focused on the emissions from the regions A and B marked in Fig. 4(a), which correspond to the GaAs substrate and cap-arm-well, respectively. Figure 4(c) shows the temperature dependence of emission patterns observed at the center energies corresponding to the emission of GaAs substrate (c-1) and those of the cap-arm-well (c-2,3,4). At 5 K, substantial amount of emissions were observed from the GaAs bulk in region A and the cap-arm-well in the region B as shown in (c-1) and (c-2), which indicates that the holes injected from the stem wells overflowed from the active region and were distributed widely throughout the arm well. The emission from the cap-arm-well in region B was observed at whole the operating temperatures up to 110 K as seen in (c-3) and (c-4) of Fig. 4(c).

The optimal $J_{th}$ of 2.1 mA and $\eta_{th}$ of 0.9% obtained at 100 K were much worse than that in a T-wire lasers having a different current-injection scheme [5]. This is probably because the current-injection efficiency, i.e., the ratio of current injected into T-wire to total current, was not optimized but was low. In fact, as shown in Fig. 4(c), injected holes are distributed widely in the arm well on (001) cladding and cap layers, which means that the centre of p-n junction was not on the wire. Therefore, further adjustment of the structure is required to improve current-injection efficiency.

4. Conclusion

In summary, we achieved cw single-mode lasing at 5–110 K in current-injection T-wire lasers with perpendicular p- and n-doping layers. We obtained the optimal operation with a low threshold current of 2.1 mA and a high differential quantum efficiency of 0.9% at 100 K. The lasers showed interesting lasing characteristics that the threshold current and differential quantum efficiency were improved with increasing temperature up to 100 K. From the microscopic-EL imaging measurements, we found that the lasing properties were most likely attributed mainly to the temperature dependence of current-injection efficiency affected by overflow of holes.

This work was partly supported by a Grant-in-Aid from the MEXT, Japan.

References