Low-Threshold Current-Injection Single-Mode Lasing in T-shaped Quantum Wires with Parallel Doping Layer

Shu-man LIU, Masahiro YOSHITA, Makoto OKANO, Toshiyuki IHARA, Hirotake ITOH and Hidefumi AKIYAMA
Institute for Solid State Physics, University of Tokyo, and CREST, JST, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan
Loren N. PFEIFFER, Ken W. WEST, and Kirk W. BALDWIN
Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974
E-mail address: lsm@issp.u-tokyo.ac.jp

Abstract: CW single-mode lasing from 30K to 70K with the lowest threshold current of 0.27mA has been demonstrated in 20-period T-shaped quantum-wire laser diodes with parallel p and n doping layers.

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1. Introduction

Quantum wire (QWR) lasers are expected to exhibit improved performance including low threshold currents, narrow spectral linewidths and reduced temperature sensitivity due to the particular one-dimensional active region[1]. Thus quantum wire laser diodes are one subject of intensive research and have been realized by several groups during the past decade[2-4]. However, the expected superior performances have not yet been practically realized because of the difficulty in preparation of highly homogenous QWR structure. T-shaped quantum wires (T-wire) can be produced with a quality comparable to that of quantum wells by the cleave-edge-overgrowth (CEO) method in molecular beam epitaxy (MBE), and allows size less than the Bohr radius of the exciton and small thickness fluctuations, hence exhibits confinement in the 1D quantum limit[5-8]. In 1994, Wegscheider *et al.* [9] reported low threshold currents of 0.4-0.8 mA at 4 K for multimode emission from 15-period T-wire laser diodes with perpendicular p and n doping layers. Here, we report the lowest-threshold T-wire lasers based on a new injection scheme introducing parallel p and n doping layers. We also present detailed experimental studies of the current-injection T-wire lasers via micro-photoluminescence (microPL) spectroscopy and imaging, and show that through proper design of current injection path it is possible to achieve low threshold lasing.

2. Fabrication

Figure1 shows a schematic view of a laser structure. 20-period GaAs/AlGaAs quantum wires formed at T-shaped intersections of 14-nm-thick stem wells and a 6-nm-thick arm well are fabricated by the CEO method with MBE. The quantum wires are embedded in the core of the T-shaped optical waveguide surrounded by the three cladding layers. Si-doped (C-doped) multiple quantum wells (MQWs) as an n-type (p-type) injection layer were grown at the bottom (top) of the slab waveguide during the first growth. By this scheme, both electrons and holes are injected into the arm well and then flow into the T-wires, which is different from Ref.[4]. A laser bar with 500 μm cavity length was cut from the wafer by cleavage and the cavity facets were coated by 50-nm-thick (front facet) and 200-nm-thick gold films.

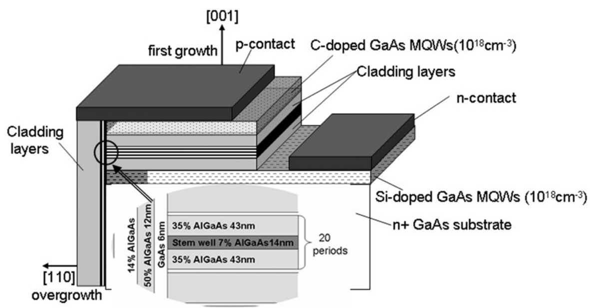

Fig.1 Schematic structure of a T-shaped quantum-wire laser sample with 20 wires of 14 nm by 6 nm size.

3. Results

Figure 2 shows typical microPL spectra obtained by scanning across an entire 7-μm-thick sample. A simplified schematic cross-section of the sample is shown in the inset. From the microPL spectra, we can determine the recombination energy in 1D T-wire, 2D stem wells, C-doped and Si-doped injection as 1.565, 1.644, 1.586 and 1.600 eV, respectively. The narrow FWHM of ~ 0.9 meV and the small energy split of ~1.8 meV of the dominant 1D exciton peak indicate small thickness fluctuation of the

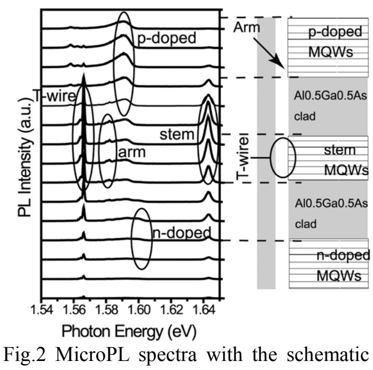

Fig.2 MicroPL spectra with the schematic cross-section

overgrown arm well.

Under cw current injection operation, single mode lasing was observed between 30 and 70 K with the threshold current from 0.27 to 0.70 mA and the differential quantum efficiency of from 12% to 8%. A typical light-current-voltage characteristic at 30 K is shown in Fig. 3a. High-resolution electroluminescence (EL) and lasing spectra below and above threshold at 30 K are shown in Fig.3b. The modulation in the EL intensity below lasing threshold shows Fabry-Perot cavity modes with the mode spacing of 0.28 meV (0.16 nm). Above threshold, a narrow peak develops at 1.555eV in the center of the spontaneous emission band. The largest shift as the current increases to 1.5 mA is 2 meV, showing the stability of the lasing energy from our T-wire laser diodes. No emissions from stem wells have been observed in all the EL spectra below and above threshold. The threshold injection current of 0.27 mA for 20-period 500-μm-long T-wires represents 14 μA per single-wire, which is to our knowledge, the lowest lasing threshold current reported for GaAs quantum wires.

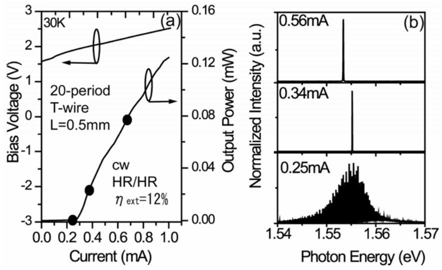

Fig.3 a) A typical voltage-current-output characteristic at 30 K; b) High-resolution emission spectra at three input currents.

We also investigated the samples over a temperature range from 5 to 100 K by EL imaging measurement.. Figure 4 shows near-field EL images of a sample at 0.35 mA, 30 K and 0.38 mA, 5K, respectively. The signal is the unfiltered emission of the sample. It is clear that at 30 K, when the current injection is above threshold, the lasing pattern is located at the center of T-wire region, while at 5 K under the current injection of 0.38 mA, the EL from the p-doped layer becomes distinct. Similar EL emission from p-doped layer has been observed at temperatures below 30 K.

We discuss further the carrier injection, recombination based on a schematic energy band diagram shown in Fig.5. Once entering the arm well, electrons can move electrons to the T-wire active region with lowest energy. However, lower mobility of hole in injection layer is believed to make the injection of electron and hole into T-wires nonequilibrium. When the forward bias is high enough, electrons have large probability to pass T-wires. Therefore, strong emission from the C-doped layer is observed at 5 K when the current is 0.38 mA. To avoid such hole freezing, modulation doping will help in obtaining enough hole mobility even at 5 K. At high temperature gain reduction is usually caused by thermal smearing of carrier population. The optical confinement factor is very small ($4.6x10^{-3}$) [10] in our T-shaped structure, thus it is possible that the peak gain can not compensate all the losses even with high material quality. Increasing the number of T-wires in the active region might help to increase the optical confinement factor.

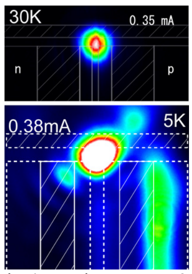

Fig.4 EL images at 30 K, 0.35 mA and 5 K, 0.38mA.

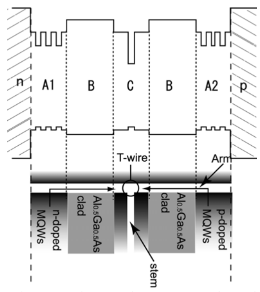

Fig.5 Schematic energy band diagram.

4. Conclusions

We have presented a low-threshold current-injection laser using T-shaped GaAs/AlGaAs quantum wires as gain medium with a simple current-injection scheme. We have demonstrated continuous-wave single mode lasing at 1.555eV with threshold of 0.27mA and differential quantum efficiency of 12% at 30K and discussed the carrier injection and recombination at various temperature range based on EL imaging measurements.

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