GaInAsP/InP long-wavelength lasers with strain-compensated quantum-wire active regions and SiO₂/semiconductor reflectors

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Abstract: GaInAsP/InP strain-compensated multiple-quantum-wire lasers (wire widths of 19 nm and 27 nm in a period of 100 nm) with SiO₂/semiconductor reflectors were realized by electron-beam lithography, CH₄/H₂ reactive ion etching and two-step organometallic vapor-phase-epitaxial growth processes. As a result, the threshold current densities of these quantum-wire lasers were lower than those of quantum-film lasers prepared on the same initial wafer and oscillations from the transition between the ground levels were observed at room temperature.

Keywords: quantum-wire laser, strain-compensated quantum-well structure, GaInAsP/InP, CH₄/H₂ RIE, OMVPE regrowth

Classification: Photonics devices, circuits, and systems

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1 Introduction

For the high-performance operation of GaInAsP lasers consisting of low-dimensional systems, not only better crystal quality but also better position controllability are very attractive, particularly for those lasers combined with distributed feedback (DFB) cavities [1, 2, 3, 4].

By using a two-step growth method, which combines electron-beam (EB) lithography, CH₄/H₂ reactive ion etching (RIE) and organometallic vapor-phase-epitaxial (OMVPE) regrowth, we realized a reliable room-temperature (RT) continuous-wave (CW) operation of strain-compensated (SC) quantum-wire (Q-Wire) lasers (wire width of 23 nm, 5 stacked quantum wires) without any serious performance degradation even after more than 14,000 h. However, a lower threshold current density than those of quantum-film (Q-Film) lasers could not be obtained due to the oscillation from the transition between the excited levels [3, 4].

In this paper, we report the lasing characteristics of multiple-quantum-wire lasers (wire widths of 19 nm and 27 nm) with a SiO₂/semiconductor reflector, which was adopted to decrease the threshold carrier density by reducing the mirror loss.

2 Fabrication

An SC-multiple-quantum-well (MQW) structure was prepared on a (100) p⁺-InP substrate as an initial wafer by an OMVPE technique. Introduction of the SC-QW structure consisting of compressively strained (CS) wells and tensile-strained (TS) barrier layers is very useful for the reduction of nonradiative recombinations at etched/regrown interfaces and the suppression of three-dimensional stress induced during etching and InP embedding regrowth processes [5, 6]. The initial wafer consists of five Ga_{0.22}In_{0.78}As_{0.81}P_{0.19} 1% CS-QW layers (undoped, 7 nm thick) sandwiched by six Ga_{0.25}In_{0.75}As_{0.50}P_{0.50}

–0.15% TS barrier layers (undoped, $\lambda_g = 1.2 \mu\text{m}$, 12 nm thick). The Q-Wire structure was fabricated from this initial wafer by the previously reported method [1, 4]. Figure 1 shows cross-sectional scanning electron microscope (SEM) images of Q-Wire active regions with a period (Λ) of 100 nm. The typical wire widths ($\overline{W}$) were measured to be (a) 19 nm and (b) 27 nm, which correspond to the in-plane space filling factors of the active region ($\rho = \overline{W}/\Lambda$) of 0.19 and 0.27, respectively. Hence, we denote these lasers as Q-Wire19 and Q-Wire27, respectively.

After the fabrication of the Q-Wire structures, 10 pairs of SiO₂/semiconductor mirrors consisting of first-order deeply etched distributed Bragg reflector (DBR) structures (period of DBR (Λ_{DBR}): 395 nm, gap width: 275 nm, semiconductor width (Λ_{semi}): 120 nm) and stripe mesa (stripe width (W_s) = 3 μm) were fabricated by EB lithography and CH₄/H₂ RIE, as shown in Fig. 1 (c) [7].

Fig. 1. SEM images of (a) Q-Wire19, (b) Q-Wire27 and (c) SiO₂/semiconductor reflectors.

3 Lasing characteristics

Figure 2 shows (a) a summary of fundamental properties such as cavity length (L), wavelength (λ), threshold current (I_{th}), threshold current density (J_{th}) and differential quantum efficiency (η_d) and (b) the light output characteristics of Q-Wire19, Q-Wire27 and Q-Film lasers prepared on the same initial wafer under a pulsed condition at RT. The laser performance was relatively poor compared with previously reported ones due to difficulties in the fabrication of the top electrode. However, the threshold current densities of these Q-Wire lasers are lower than that of the Q-Film laser, which can be

attributed to a volume effect of the active region. Since the differential quantum efficiencies of these Q-Wire lasers are similar to that of the Q-Film laser, there is no serious increase in optical loss due to the fabrication process.

(a)

	L (μm)	λ (μm)	I_{th} (mA)	J_{th} (A/cm ²)	η_d (%)
Q-Wire19	910	1.48	39	1425	26
Q-Wire27	805	1.50	31	1260	20
Q-Film	840	1.58	52	2040	20

Fig. 2. (a) Summary of fundamental properties and (b) $L - I$ characteristics of Q-Wire19, Q-Wire27 and Q-Film lasers under pulsed condition at RT.

Figure 3 shows the lasing spectrum and the spontaneous emission spectrum of Q-Wire19 at RT. In the case of previously reported Q-Wire lasers with a wire width of 18 nm in a period of 80 nm [8], the lasing wavelength ($\lambda = 1.453 \mu\text{m}$) was approximately 50 nm shorter than the spontaneous emission peak wavelength ($\lambda = 1.501 \mu\text{m}$) and almost coincided with the theoretical emission wavelength ($1.448 \mu\text{m}$) for the first excited levels.

On the other hand, in the case of Q-Wire19, while a slight shift (21 nm) between the lasing wavelength ($1.483 \mu\text{m}$) and the spontaneous emission peak wavelength ($1.504 \mu\text{m}$) was observed, the lasing wavelength did not coincide with the theoretical emission wavelength ($1.454 \mu\text{m}$) for the first excited levels (dashed line). Accordingly, the oscillation from the transition between the ground levels could be obtained which is attributed to the reduction in the threshold carrier density with the introduction of the SiO₂/semiconductor reflector. However, the threshold current densities of these devices were not

Fig. 3. Lasing spectrum and spontaneous emission spectrum for Q-Wire19 at RT. Dashed line indicates the emission wavelength from the first excited levels calculated by theoretical analysis.

satisfactory, which might be attributable to a difficulty in the fabrication process of narrow mesa-stripe structures.

4 Conclusion

We realized GaInAsP/InP strain-compensated multiple-quantum-wire lasers (wire widths of 19 nm and 27 nm in a period of 100 nm) with SiO₂/semiconductor reflectors using EB lithography, CH₄/H₂ RIE and OMVPE regrowth. Consequently, the threshold current densities of these quantum-wire lasers were lower than those of quantum-film lasers. The differential quantum efficiency of these quantum-wire lasers was also comparable to that of quantum-film lasers. Therefore, these results indicate that this fabrication process is very promising for the realization of high-performance quantum-wire and quantum-box lasers based on the GaInAsP/InP system.

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