1.5 μm Wavelength Strain-Compensated GaInAsP/InP 5-Layered Quantum-Wire Lasers by Low-Damage CH_4/H_2 Reactive Ion Etching Process

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Abstract

1.5-μm-wavelength strain-compensated GaInAsP/InP 5-layered quantum-wire lasers with the wire width of 23 nm in the period of 80 nm were realized for the first time by EB lithography, CH_4/H_2 reactive-ion-etching and organo-metallic-vapor-phase-epitaxy regrowth. The threshold current density of 774 A/cm^2 and differential quantum efficiency of 40% were obtained under a pulsed condition at room temperature. From measurement of spontaneous emission spectra, the blue shift at the peak wavelength was 38 meV, which was much larger than a calculated value, and the FWHM was almost constant at temperatures from 100 K to 253 K, indicating a lateral quantum confinement effect. Finally, no noticeable degradation in the spontaneous emission efficiency was observed within measurement temperature range up to 85 °C.

I. Introduction

Narrow gain spectrum feature of quantum-wire (Q-Wire) and quantum-box (Q-Box) structures is very attractive for high-performance operation of semiconductor lasers.[1]-[3] Among various fabrication methods,[4]-[7] we have been investigating a fabrication process which combines electron beam (EB) lithography, wet/dry etching and organo-metallic-vapor-phase-epitaxial (OMVPE) regrowth because of better size and position controllability than those of other methods.[8][9] By using this process, we realized strain-compensated (SC) five-quantum-well (5QW) wirelike lasers with the wire widths of 43 nm and 70 nm, which had lower threshold current density and higher differential quantum efficiency than those of quantum-film (Q-Film) lasers prepared on the same wafer up to 80 °C.[10][11]

In this paper, we would like to report lasing properties of SC 5-layered Q-Wire lasers with the wire width of 23 nm. The spontaneous emission efficiency below the threshold was almost comparable to that of the Q-Film lasers up to 85 °C, that revealed low-damage property of the etched/regrown interfaces.

II. Lasing Properties

First, an SC multiple-quantum-well (MQW) structure was prepared on a (100) p$^+$-InP substrate as an initial wafer. It consists of a p-InP buffer layer (N_A=5×10^{17} cm^{-3}, 2 μm thick), an undoped $Ga_{0.22}In_{0.78}As_{0.47}P_{0.53}$ optical confinement layer (OCL: λ_g=1.2 μm, 170 nm thick, lattice matched to InP), five $Ga_{0.22}In_{0.78}As_{0.81}P_{0.19}$ 1% compressively-strained (CS) quantum-well (QW) layers (undoped, 7 nm thick) sandwiched by six $Ga_{0.25}In_{0.75}As_{0.50}P_{0.50}$ −0.15% tensile-strained barrier layers (undoped, λ_g=1.2 μm, 12 nm thick), a GaInAsP OCL layer (λ_g=1.2 μm, 45 nm thick) and an InP cap layer (10 nm thick). We prepared two patterns on the same wafer, i.e. wire pattern with the period of 80 nm and a nonpatterned region completed to be Q-Film lasers for comparison. Conditions used in this process, such as etching, cleaning of the etched surface and regrowth are almost the same as those described in our previous papers.[9][10] Finally, we formed a 15.4-μm-wide mesa stripe structure.

Figure 1 shows cross-sectional scanning electron microscope (SEM) view around the Q-Wire active region with a period (Λ) of 80 nm and its schematic diagram. The typical wire width (W) was measured to be 23 nm, hence, this laser is denoted by Q-Wire23.

Figure 2 shows light output characteristics of the Q-Wire23, the Q-Film lasers prepared on the same wafer and the wirelike laser with the wire width of 43 nm (Wire43, for short) in the period of 100 nm under a pulsed condition (1 μs width, 1 KHz repetition) at room temperature (RT). Laser structures and lasing characteristics, such as stripe width (W_s), cavity length (L), lasing wavelength (λ), threshold current (I_{th}), threshold current density (J_{th}) and differential quantum efficiency (η_d) of these lasers are summarized in Table 1. The threshold current density of the Q-Wire23 (774 A/cm^2) was about a half that of 2-layered Q-Wire laser fabricated from a CS-MQW wafer,[9] because an adoption of the SC-MQW structure as the initial wafer is, we believe, very effective for better etched/regrown interface. However, it was about 2 times higher than that of the Wire43 while the differential quantum efficiency of the Q-Wire23 was almost equal to that of other lasers.

This can be attributed to smaller optical confinement factor of the active region and broader emission spectrum than that of the Q-Film structure due to a size fluctuation of quantum-wires, or non-radiative recombinations at the etched/regrown interfaces, as explained in sections III and IV.

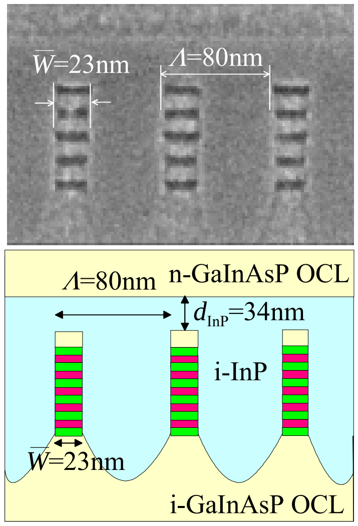


Fig. 1 Cross-sectional SEM view.

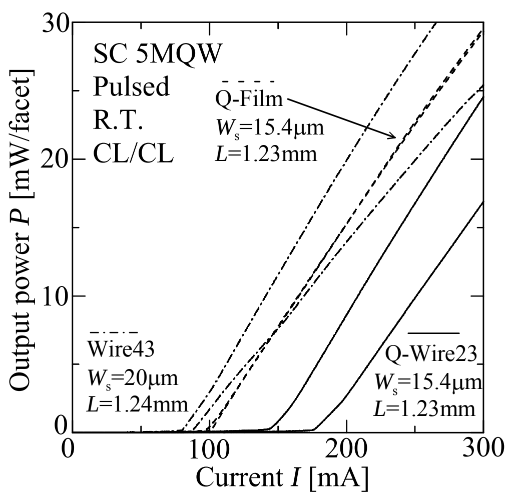


Fig. 2 I-L characteristics of Q-Wire23, Wire43 and Q-Film lasers.

Table 1 Lasing characteristics

	L [mm]	λ [μm]	I_{th} [mA]	J_{th} [A/cm^2]	η_d [%]
Q-Film W_s=15.4μm	1.23	1.57	98.8	524	38.3
	1.23	1.57	98.5	522	38.0
Wire43 W_s=20μm	1.24	1.53	78.9	318	41.9
	1.24	1.53	86.6	349	30.3
Q-Wire23 W_s=15.4μm	1.23	1.49	146	774	39.9
	1.23	1.49	181	961	34.4

Figure 3(a) shows the temperature dependence of the threshold current density of the Q-Wire23 and the Q-Film laser prepared on the same wafer under a pulsed condition from 83 K to 358 K. In our previous work,[11] the lower threshold current density of the Wire43 than that of Q-Film lasers prepared on the same wafer was obtained up to 358 K. Furthermore, it steeply decreased with reducing the temperature and became almost 40% of that of the Q-Film laser at T<220 K which corresponds to the value estimated from the volume of the active region. Since the full width at half maximum (FWHM) of electro luminescence (EL) spectrum of the Wire43 was almost the same as that of the Q-Film laser within the measured temperature range, this low threshold property is attributed to a volume effect of the active region.

In this work, the threshold current density of the Q-Wire23 was higher than that of the Q-Film laser at T>203 K. Even at temperatures between 100 ~ 200 K, J_{th} of Q-Wire23 was more than 2 times higher than the value estimated by taking into account of the volume effect.

Figure 3(b) shows the temperature dependence of differential quantum efficiency (η_d) of the Q-Wire23 and that of the Q-Film laser. η_d of the Q-Wire23 was higher than that of the Q-Film laser up to 343 K. This result indicates that an optical absorption loss of the Q-Wire23 is almost the same as that of the Q-Film laser within measured temperature range and there is no excess loss introduced by the etching/regrowth process.

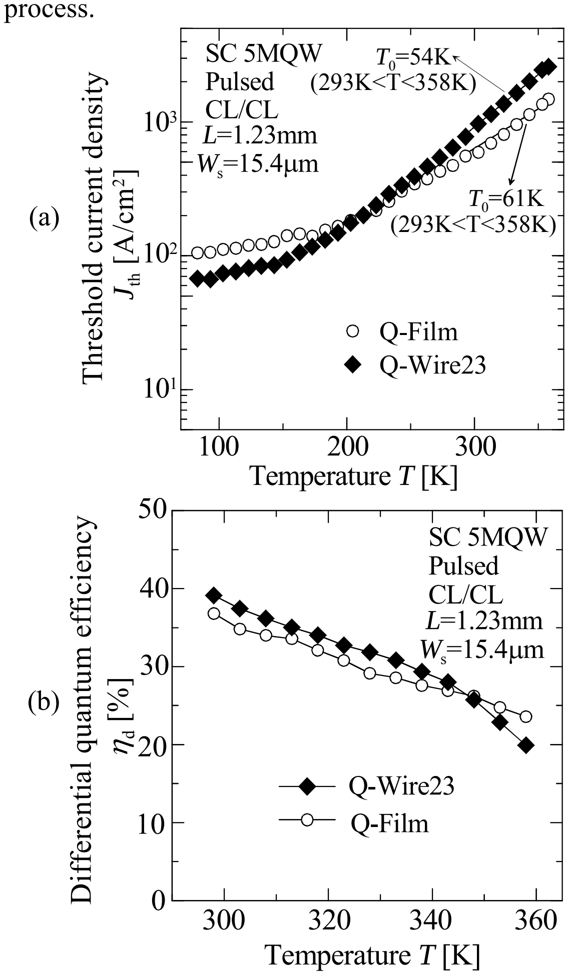


Fig. 3 Temperature dependence of (a) threshold current density and (b) differential quantum efficiency.

III. Measurement of spontaneous emission spectra

The spontaneous emission spectrum of the

Q-Wire23 was compared with that of the Q-Film laser at a low bias current level (J/ρ=111 A/cm^2) at 293 K as shown in Fig. 4(a). The blue shift at the peak wavelength in spontaneous emission spectra was estimated to be 38 meV, which was 23 meV larger than a theoretical value (15 meV) by assuming the heavy hole effective mass of m_h^*=0.0488.[12] The shift is caused by not only a lateral quantum confinement effect but also by a three-dimensional compressive-strain effect with an incomplete strain compensation. The FWHM of the Q-Wire23 (50 meV) was 6 meV wider than that of the Q-Film laser (44meV).

Figure 4(b) shows temperature dependences of the FWHM of these lasers at the same current levels normalized by the volume of active regions. The FWHM of the Q-Film laser widened almost linearly with an increase of temperature, while that of the Q-Wire23 was almost constant from 100 K to 253 K and steeply increased at room temperature probably due to a band filling effect. At 100 K, the FWHM of the Q-Wire23 (46 meV) was 20 meV larger than that of the Q-Film laser (26 meV), this can be a reason why the volume effect was not obtained in the threshold characteristics as shown in Fig. 3(a).

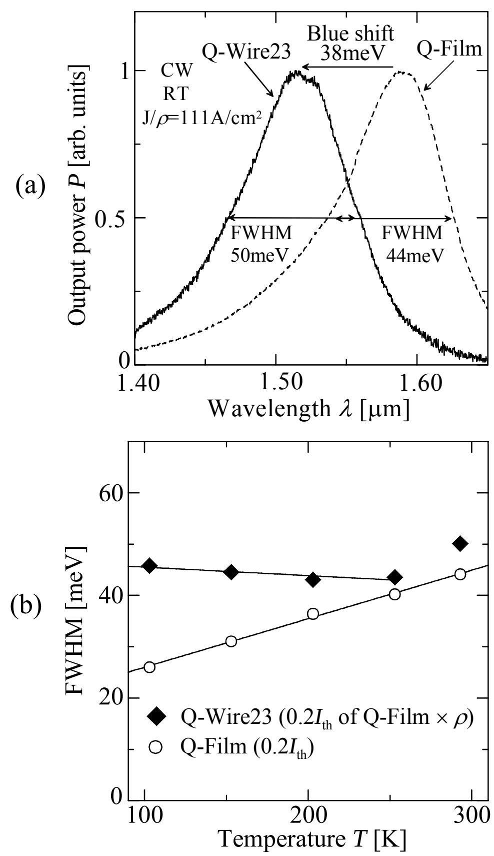


Fig. 4 (a) Spontaneous emission spectra and (b) Temperature dependences of FWHM of spontaneous emission spectra.

IV. Damage at etched/regrown interface

Next, we measured the light output characteristics of the Q-Wire23, the Wire43 and Q-Film lasers at sufficiently low bias current levels so as to evaluate a non-radiative recombination velocity at the etched/regrown interface of the SC-5-layered Q-Wire structure. As can be seen in Fig. 5, the spontaneous emission efficiency (slope efficiency of *L-I* curve) of the Q-Wire23 was around 80% or higher than that of Q-Film lasers.

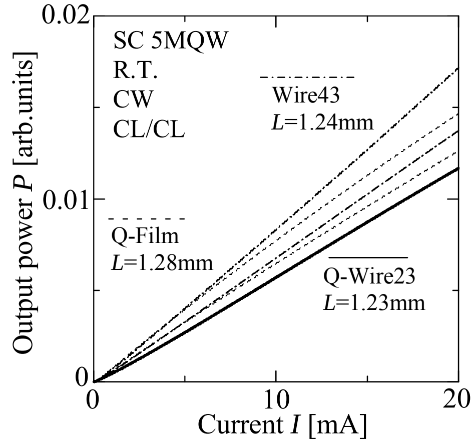


Fig. 5 L-I curves below threshold.

The product of the surface recombination velocity (S) at etched/regrown interfaces and the carrier lifetime (τ) was estimated from the relation of the spontaneous emission efficiency $\eta_{\text{spon,Wire}}$ of a laser with a wirelike active region normalized by that of a Q-Film laser $\eta_{\text{spon,Film}}$, which can be, by assuming that the wire width is much narrower than carrier diffusion lengths, written as:[13]

$$\frac{\eta_{\text{spon,Wire}}}{\eta_{\text{spon,Film}}} = \frac{1}{1+\dfrac{2\cdot S\cdot \tau}{W-2W_{\text{d}}}} \quad , \qquad (1)$$

where W is the wire width, and dead layer width was neglected (W_{d}=0).[14] By using $\eta_{\text{spon,Film}}$ of 2 Q-Film lasers in Fig. 5, $S\cdot\tau$ was estimated from eq. (1) to be less than 3 nm which was much smaller than that of the CS-5MQW wirelike structure as shown in Fig. 6.[15] This improvement is, we believe, caused by suppression of a strain relaxation at etched/regrown interfaces by adopting an SC-MQW structure as the initial wafer.

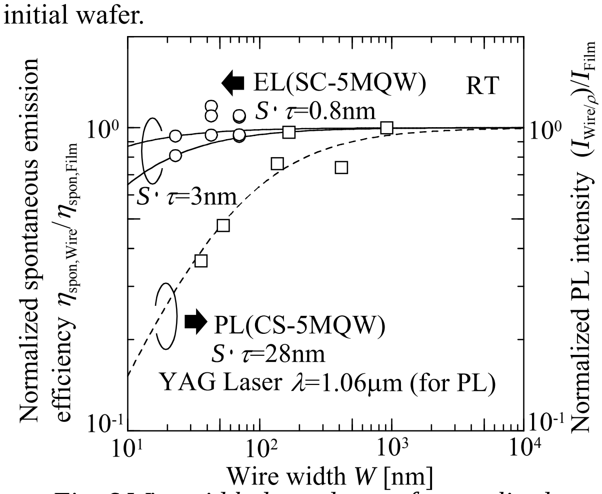
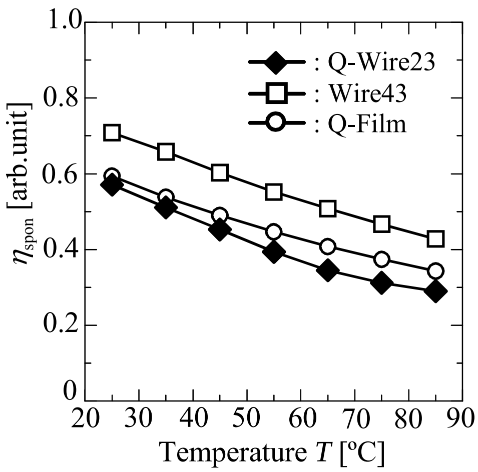


Fig. 6 Wire width dependence of normalized spontaneous emission efficiency.

Finally, temperature dependences of spontaneous emission efficiency of these lasers were compared from 25 °C to 85 °C. As can be seen in Fig. 7(a), although there was no remarkable difference between the temperature dependences of the Wire43 and the Q-Film laser, that of the Q-Wire23 slightly decreased at higher temperatures. Figure 7(b) shows the temperature dependences of the relative spontaneous emission efficiency of the Q-Wire23 and the Wire43 normalized by that of the Q-Film laser. As can be seen, the ratio of the Q-Wire23 at 85 °C was around 88% of that at 25 °C. This fact indicates low-damage property of the etched/regrown interface of the SC GaInAsP/InP Q-Wire structure up to 85 °C. Therefore, higher threshold current density of the Q-Wire23 than that of the Q-Film laser as shown in Fig. 3(a) is mostly attributed to lower modal gain based on a size fluctuation and smaller volume of the active region, not to the poor etched/regrown interface.

(a)



(b)

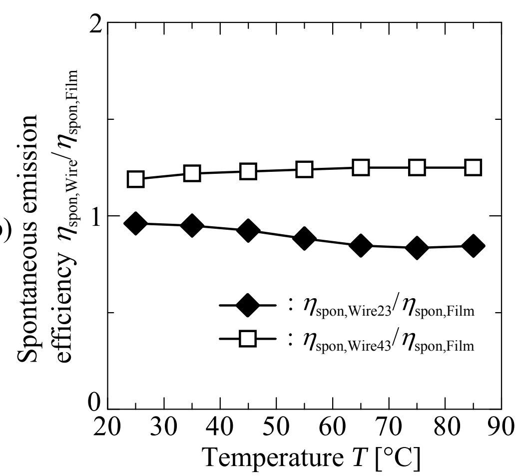


Fig. 7 Temperature dependences of spontaneous emission efficiency (a) $d\eta_{spon}/dT$ and (b) $\eta_{spon,Wire}/\eta_{spon,Film}$.

V. Conclusion

We realized 5-layered GaInAsP/InP quantum-wire lasers for the first time by using CH_4/H_2-RIE and 2-step OMVPE growth process. Low-damage feature of this fabrication process was experimentally confirmed from their spontaneous emission efficiency and differential quantum efficiency comparable to those of quantum-film lasers with the same active region.

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