Fabrication of Nano-Structures Using EB-Lithography and Its Application to Long-Wavelength Quantum-Wire Lasers

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Abstract: It is important to fabricate high density and high uniformity nano-structures for the realization of quantum wire lasers. In this work, 1.5μm-wavelength GaInAsP/InP quantum wire lasers were fabricated by electron beam (EB) lithography, and wet chemical etching followed by embedding organic metal vapor phase epitaxy (OMVPE) growth. The average size of resist pattern for the period of 50nm was 30.7nm and the standard deviation was approximately ±1.1nm (3.6%). Temperature dependences of the quantum wire lasers were measured and compared with the quantum film lasers fabricated on the same wafer. As the result, better lasing properties, such as low threshold current and high differential quantum efficiency of quantum wire lasers over quantum film lasers were confirmed at low temperature. The low threshold current density of 43A/cm^2 of the quantum-wire laser at 98K was obtained.

1. Introduction

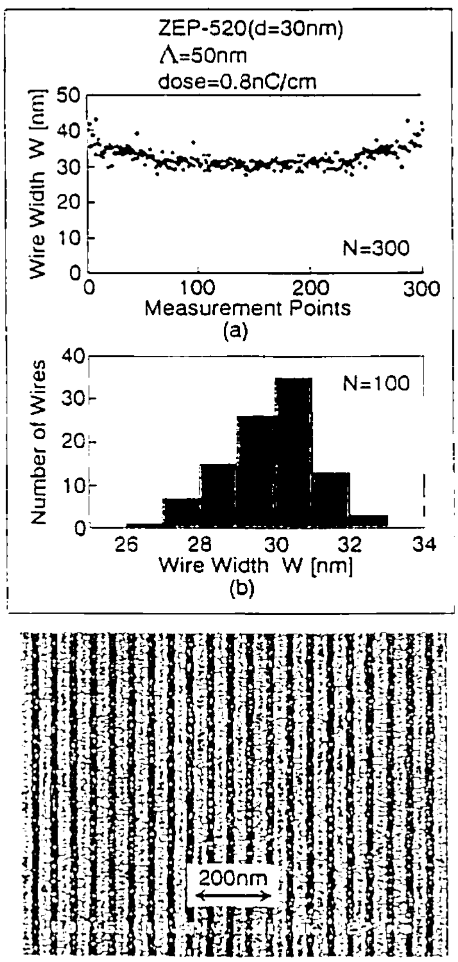
To realize giga-bit transmission system by optical interconnection between broad-bandwidth optical fiber communication and opto-electronics integrated circuits (OEICs), high performance of semiconductor lasers is expected by means of introducing quantum wire (box) as an active region for high optical gain due to the increase of carrier concentration in these structures.[1-4] Now-a-days, much work has been done for the fabrication of such devices with low dimensional quantum structures.[5-11] However due to low optical confinement factor ξ and poor size uniformity of multi-layered quantum wire active region, high performance properties, such as low threshold current and high differential quantum efficiency, for long wavelength GaInAsP/InP quantum wire lasers have not been demonstrated yet.[6,12] To solve this problem, we adopted a relatively thick compressively strained (1%CS) quantum well (10nm thick, ξ=1.3% for the quantum film, λ_{PL} =1.576μm) structure as the basic material for quantum wire structure, and a thin quantum film layer (1%CS, 5nm thick, ξ=0.6%, λ_{PL}=1.512μm) is introduced to partially support the optical confinement and gain, when the wire size becomes very narrow and the gain peak wavelength shifts close to the quantum film's gain peak. Furthermore, single mode property is obtained by introducing distributed feedback (DFB) structure in the active region as the waveguide structure[13-14]. So higher properties of quantum wire DFB lasers are expected for these advantages.

In this work, we fabricate single layer quantum wire (DFB) lasers assisted by quantum film structure, using 2-step OMVPE growth, EB-lithography, and wet chemical etching. Then we demonstrate temperature dependences of these lasers compared with those of quantum-film lasers fabricated on the same wafer.

2. Fabrication of Quantum Wire Lasers

2.1 Measurement of size fluctuation

In order to realize high performance operation of quantum wire (box) structures, it is important to control the size fluctuation within 10% (20%). The size uniformity of a quantum wire pattern formed by the EB lithography was investigated. A sample containing 300 quantum wire patterns (90μm long) was formed by JBX-5FE EBX system (JEOL) with a line dose condition of 0.8nC/cm for the grating period of 50nm and the EB-resist (ZEP-520) thickness of 30nm over SiO_2 mask layer (20nm thick)[15]. Figure 1(a) shows the size distribution of the wire width at the center portion of the sample, measured using a high resolution SEM (Hitachi S-5000). Fig.1(b) and (c) show the histogram at the center portion (for 100 wires) and the SEM image, respectively. The average size of the resist pattern was 30.7nm and the standard deviation was approximately ±1.1nm (3.6%). The standard deviation for a single wire pattern was measured to be ±1.5nm (4.9%).



(c)

Fig.1 (a)Size distribution of resist pattern of 300 wires
(b)Histogram for 100 wires
(c)SEM image at the center portion of the sample

2.2 Fabrication of Quantum Wire (DFB) lasers assisted by Quantum Film

Using this technique, we fabricated long wavelength GaInAsP/InP quantum wire lasers. Though various methods to fabricate quantum wire structures have been reported, the technique using EB-lithography and etching is better method for the position and size controllability of quantum wire and easier for the application to quantum box or DFB structure. Figure 2 shows the schematic structure and bandprofile of a quantum wire laser assisted by quantum film layer. Epitaxial layers consist of a 2-μm-thick p-InP buffer layer ($N_A=5\times10^{17}cm^{-3}$), an un-doped GaInAsP 3-step optical confinement layer (OCL) at the lower side (90nm thick), lower $Ga_{0.18}In_{0.82}As_{0.73}P_{0.27}$ compressively strained quantum well (CS-QW) layer (un-doped, 5 nm thick, 1% strain), un-doped GaInAsP barrier layer (λ_g=1.2μm, 12 nm thick), upper $Ga_{0.18}In_{0.82}As_{0.73}P_{0.27}$ CS-QW layer (un-doped, 10 nm thick, 1% strain), upper side n-GaInAsP 1-step OCL (λ_g=1.2μm, 200 nm thick, $N_D=1\times10^{18}cm^{-3}$), a 3-μm-thick n-InP cladding layer and an n-GaInAs contact layer (50nm thick) on a p-InP substrate in order to increase the hole injection efficiency[14]. Three different type samples, namely quantum wire lasers assisted by quantum film (Wire for short), quantum-wire

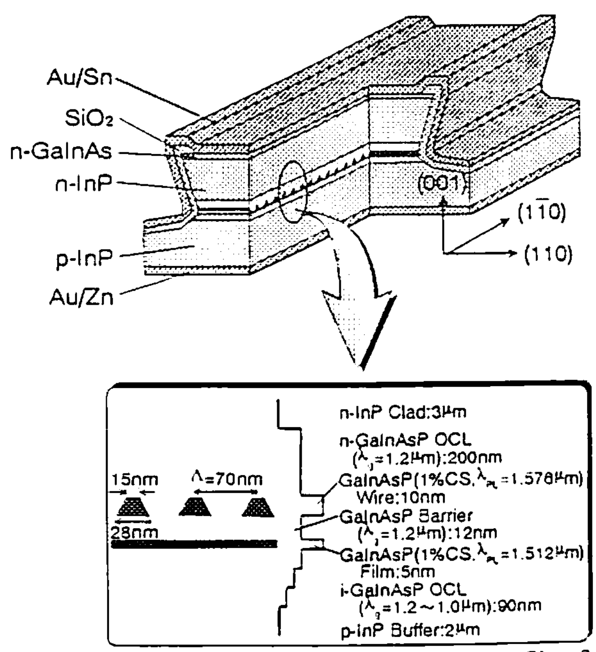


Fig.2 The schematic structure and bandprofile of a Q-Wire laser assisted by Q-Film

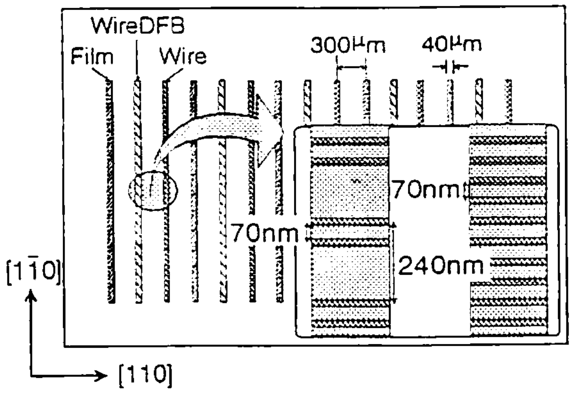
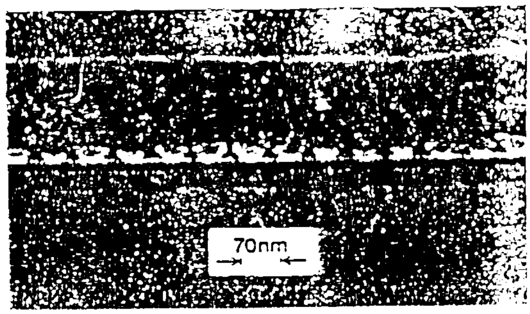


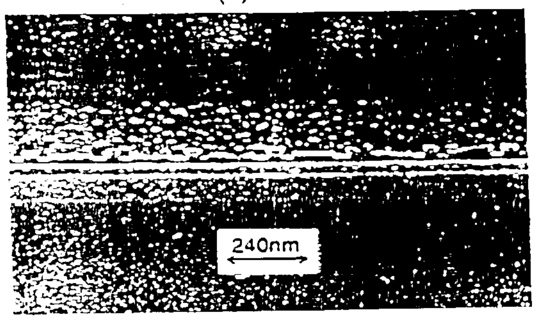
Fig.3 EB pattern

DFB lasers assisted by quantum-film (Wire DFB), and 2-layer quantum-film lasers (Film) were fabricated on the same wafer as shown in Fig.3. Here a line dose condition of was 0.8nC/cm was used for the grating period of 70nm for the 30nm thick ZEP-520 resist. Three different stripe patterns (such as Film stripe, Wire DFB stripe and Wire stripe) were formed using EB lithography. The width of these stripes were about 40μm with a grating period of 300μm, which are shown in the Fig.3. Here the direction of quantum wire structure was perpendicular to the stripe direction. Wire stripes consists of quantum wires with a period of 70nm and Wire DFB laser stripes consists of two wires in order to increase optical confinement factor of active region, with a period of 70nm between them and for grating period of 240nm. To fabricate quantum wire structure, we used two type of etchant; one was 40ppm (volume ratio) Br-methanol for mesa-etching, and the other was H_2SO_4:H_2O_2:H_2O=1:1:10 (0°C) for side-etching. After embedding OMVPE growth, high-mesa stripe laser with the stripe width of 15 μm was formed so as to select a center portion of the quantum-wire pattern with higher size uniformity.

The cross sectional SEM views of (a) Wire laser and (b) Wire DFB laser are shown in Fig.4. As can be seen, the size of the Wire laser is 15nm (top) and 28nm (bottom) with a period of 70nm, and that of the Wire DFB laser consists of two 20-30nm width wires with a period of 70nm between the wires for a grating period of 240nm. And the lower 5nm 1%CS GaInAsP layer remains as quantum film for both lasers structure .



(a) Wire



(b) Wire DFB

Fig.4 Cross sectional SEM view of (a) Wire and (b) Wire DFB laser

3. Lasing Properties of Wire (DFB) Lasers

Figure 5 shows temperature dependence of threshold current for these three kinds of lasers under pulsed injection current condition. The cavity length and the stripe width of these lasers were 860μm and 15μm, respectively. Even though threshold current of the Wire (DFB) laser was 5～10 times greater than the Film laser at room temperature, it rapidly decreased with the decrease in the temperature, and became lower than the Film laser at T<193K. At T=98K, threshold current density of the Wire laser was 43A/cm^2 (I_{th}=5.5mA) which was almost half the value of the Film laser (J_{th}=85A/cm^2 and I_{th}=11mA). The Wire DFB laser showed a similar temperature dependence, and its threshold current density was 54A/cm^2 (I_{th}=7mA) at 98K. Figure 6 shows I-L curves of the Wire laser and the Film laser at 98K. Not only low threshold current but also high differential quantum efficiency operation of the Wire laser were obtained. The threshold current (density) and differential quantum efficiency of Wire laser was 5.5mA (43A/cm^2) and 63%, respectively. Figure 7 shows temperature dependences of lasing wavelength of these three kinds of lasers. This figure clearly shows that the temperature coefficient of lasing mode in the Wire DFB laser was about 0.08nm/K and Film laser was around 0.54nm/K. From this, we also show the possibility to fabricate DFB lasers whose grating structure as quantum wire size. A large discrepancy between the temperature coefficients of lasing wavelength of the Wire laser (0.42nm/K) and the Film laser may be attributed to also band filling effect due to high threshold carrier density at around room temperature. The value of blue shift for Wire laser to Film laser was estimated at T=98K in order to eliminate band filling effect and was about less than 10meV. This value made a good agreement with the calculated value for quantum wire size of 28nm, which was equal to the mesa-bottom size of the wire structure in Fig.4(a).

The reason for poor performance of the Wire and the Wire DFB lasers at around room temperature may be due to large amount non-radiative recombination because of the imperfect interface formed during regrowth process, and low optical confinement factor ξ of the active region[19]. The low ξ causes the carrier leakage to OCL which leads to increase in threshold carrier density. In fact, the ξ of Wire laser is only 0.93% , even when the lower film was included (only upper wire, ξ=0.42%). Because the upper wire size is still large we think the lower film does not indeed assist the upper wire for optical confinement and gain.

4. Fabrication of Narrow Quantum Wire Laser

In the previous section, the value of the blue shift estimated from emission wavelength for the Wire laser was less than 10meV. This may be due to relatively wide wire width. We fabricated two kinds of quantum wire lasers having different quantum wire size. The fabrication process was the same as in the previous lasers. The wafer consists of 1% compressively strained $Ga_{0.18}In_{0.82}As_{0.73}P_{0.27}$ quantum wells (10nm thick) structure grown over (100) p-InP substrate, and the quantum wire pattern with a period of 70nm was formed. By changing the duration of wet etching process, two different kinds of quantum wire structures ($Wire_1$, $Wire_2$) were fabricated. The average size of $Wire_1$ structure was

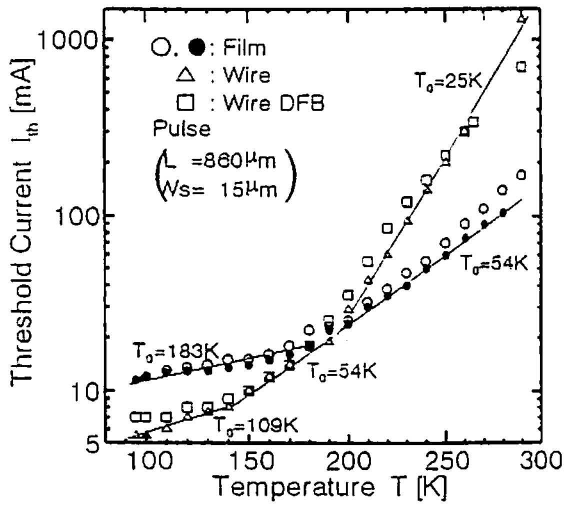


Fig.5 Temperature dependence of threshold current

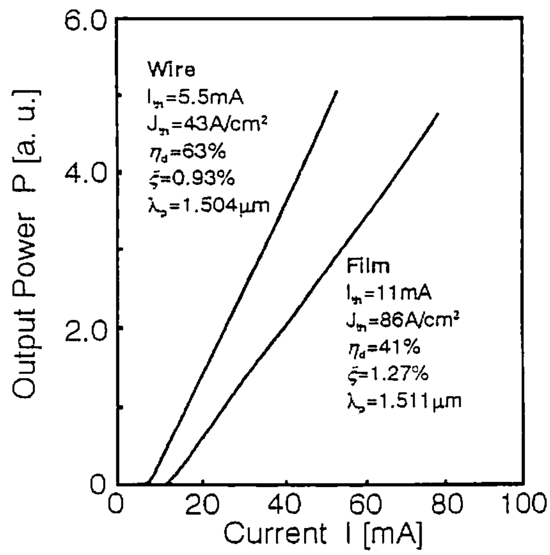


Fig.6 I-L curves at 98K

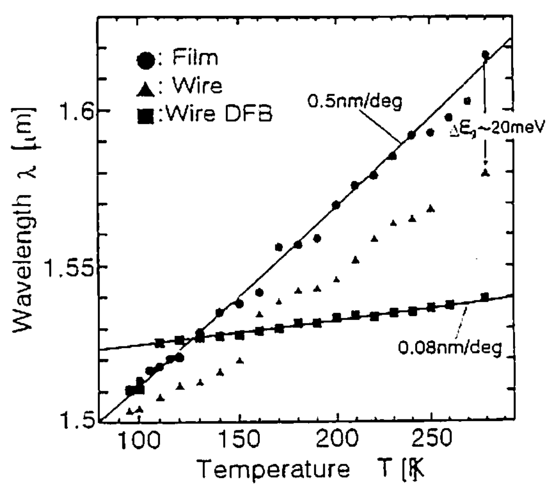


Fig.7 Temperature dependence of lasing wavelength

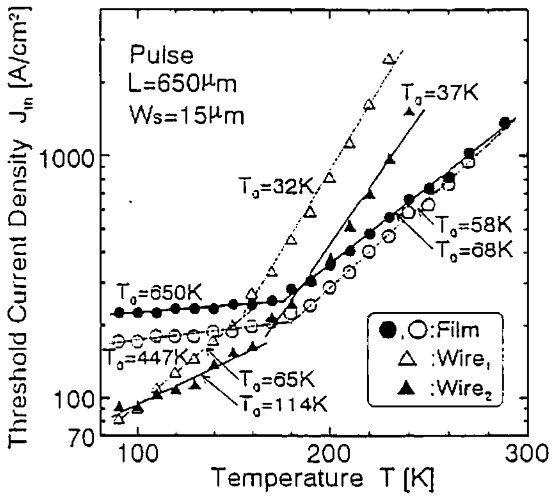


Fig.8 Temperature dependence of threshold current density

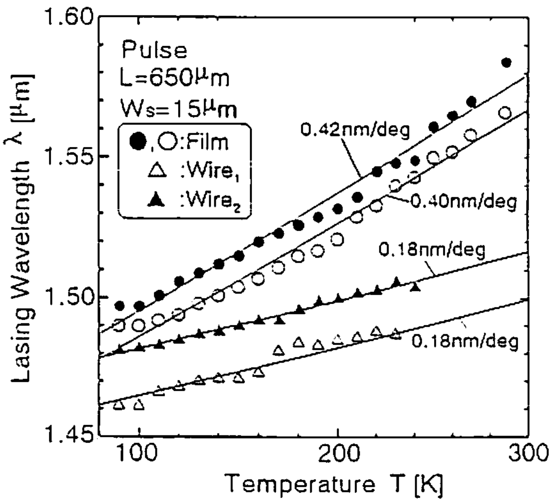


Fig.9 Temperature dependences of lasing wavelength

considered to be 15nm (12nm at mesa top and 15nm at mesa bottom) and for $Wire_2$ structure was considered to be 20nm (15nm at mesa top and 25nm at mesa bottom). Figure 8 shows the temperature dependences of threshold current density J_{th} for these two kinds of quantum wire structure and compared with that of the quantum film lasers fabricated on the same wafer. The cavity length and stripe width of these lasers were 650μm and 15μm, respectively. The threshold current density J_{th} of the quantum wire laser was lower than the quantum film laser at low temperature. At T=100K, J_{th} of quantum wire laser was almost half the value of the quantum film laser. Figure 9 shows temperature dependences of lasing wavelength. The value of blue shift for these two kinds of Wire lasers with respect to Film laser were estimated to be 20meV for $Wire_1$ and 10meV for $Wire_2$ at 90K so as to eliminate the band-filling effect. A large discrepancy between the temperature coefficients of the lasing wavelength of the Wire laser (0.18nm/deg) and the Film laser (0.4nm/deg) may be attributed to band filling effect due to higher threshold carrier density in case of the Wire laser. High threshold carrier density also leads to poor characteristic temperature in the Wire laser.

5. Conclusion

We have demonstrated temperature dependences of long-wavelength GaInAsP/InP compressively strained quantum wire (DFB) lasers with single quantum film layer using EB-lithography, wet etching, and 2-step OMVPE growth. and compared with the quantum film lasers fabricated on the same wafer. We obtained low threshold current and high differential quantum efficiency operating Wire laser at T<193K. The low threshold current density of 43A/cm^2 of the quantum wire laser at T=98K was obtained. And we also confirmed the possibility to fabricate DFB laser, whose grating structure as quantum wire size (20-30nm).

High density and highly uniform wire structure is required for superior operation at room temperature.

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