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Very low threshold single quantum well graded-index separate confinement heterostructure InGaAs/InGaAsP lasers grown by chemical beam epitaxy

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We have succeeded in preparing 1.5 μm wavelength strained-layer graded-index separate confinement heterostructure (GRINSCH) InGaAs/InGaAsP single quantum well (SQW) injection lasers by chemical beam epitaxy (CBE). These lasers have extremely low threshold current density J_{th} of 170 A/cm^2, internal quantum efficiency of 83%, and internal waveguide loss of 3.8 cm^{-1}. To the best of our knowledge, these results represent the best values obtained thus far from long-wavelength InGaAs/InGaAsP quantum well injection lasers grown by any techniques. However, despite the recent rapid reduction in J_{th}, the threshold-temperature dependence remains poor ($T_0 = 45$ K) even in these very low J_{th} GRINSCH SQW lasers.

Quantum well (QW) lasers of GaAs/AlGaAs have been intensely investigated in the last decade.[1] The most commonly used structure is the graded-index separate confinement heterostructure (GRINSCH).[2] This design results in highly efficient, extremely low threshold lasers, capable of very high power operation. Their internal loss is characteristically low. Single quantum well GRINSCH lasers with threshold current densities J_{th} of ~ 150 A/cm^2 are routine and ~ 50 A/cm^2 are not uncommon today.[3–7]

In the last few years, there has also been very significant progress in the preparation of high-quality InGaAs/InGaAsP quantum well lasers.[8–14] However, unlike the GaAs/AlGaAs quantum well lasers, the performance improvement has not yet been as dramatic. Recently, Thijs *et al.*[15] using low-pressure metalorganic vapor phase epitaxy (MOVPE), succeeded in growing strained-layer 1.5 μm wavelength GRINSCH QW lasers having minimum threshold current densities of 380 and 200 A/cm^2 for 4QW and 1QW, respectively. Simultaneously, Tsang *et al.*[16] also reported threshold current densities of 370 A/cm^2 and an internal quantum efficiency of 90% for 1.5 μm wavelength strained-layer 4QW lasers but with the simple SCH design grown by chemical beam epitaxy (CBE).[17] In this letter, we report the first successful preparation by CBE of very low threshold single quantum well GRINSCH InGaAs/InGaAsP lasers.

The epitaxial layers were grown on a (100) oriented InP substrate using a modified Riber CBE 32 and similar procedures described previously.[18] However, there is a major change in growing the *p*-doped InP. Instead of using evaporated Be as the *p*-type dopant as in all prior CBE-grown devices,[17] we introduced the use of diethylzinc (DEZn) as a gaseous dopant for the first time in CBE-grown devices. Though Be has been the only *p*-type dopant in InP used in CBE thus far, it proves to be difficult. Surface morphology degrades when net hole concentration approaches 1×10^{18} cm^{-3} unless the epilayer is grown at low temperatures (~ 500 °C). Because of this difficulty, we investigated Zn doping in InP using DEZn during CBE. A detailed report has been submitted elsewhere.[19] Contrary to the common concern, we found no Zn "memory effect" in our system. Further, secondary-ion mass spectrometric measurements indicated that serious Zn diffusion occurred only when the Zn concentration was higher than $\sim 1.5\times10^{18}$ cm^{-3} irrespective of the growth temperature (490–540 °C) used. On the other hand, for Zn concentrations below this value, very abrupt Zn profiles were obtained with some diffusion occurring only at high growth temperatures.

The GRINSCH design consists of a two-step graded InGaAsP alloys of equivalent wavelengths, 1.15 μm (thickness = 85 nm) and 1.25 μm (thickness = 20 nm) on either side of the single quantum well. The $In_{0.6}Ga_{0.4}As$ quantum well has a thickness of 2.7 nm and is under slight compressive strain. Previously,[16] we have determined that for CBE-grown MQW lasers, the optimal strain is to have an InAs mole fraction $x \approx 0.6$–0.65. This InAs mole fraction x is smaller than that employed by Thijs *et al.*[15] in their single quantum GRINSCH lasers. In addition, they also used a three-step graded GRINSCH design. To further reduce the J_{th}, additional optimization specifically for single quantum well GRINSCH design is needed. The *n*-InP buffer layer and the *p*-InP cladding layer were typically ~ 0.7 and 1.8 μm, respectively. A p^+-InGaAsP (1.25 μm composition) top layer served for ohmic contact formation. At each layer interface, growth was interrupted for 2–5 s by switching the group III metalorganic flows into the vent leaving the substrate surface stabilized by the hydride gas(es) characteristic of the subsequent layer.

In this experiment, thermal Sn was still employed as the *n*-type dopant. Recently, we have also succeeded in replacing the thermal Sn doping with tetraethyltin, thus accomplishing a totally vapor-source CBE technique. This makes the CBE technology even more compatible with the MOVPE technology. In fact, it should be considered as a high-vacuum MOVPE technique.

For broad-area threshold current density evaluation, 50-μm-wide oxide-stripe lasers were fabricated with dif-

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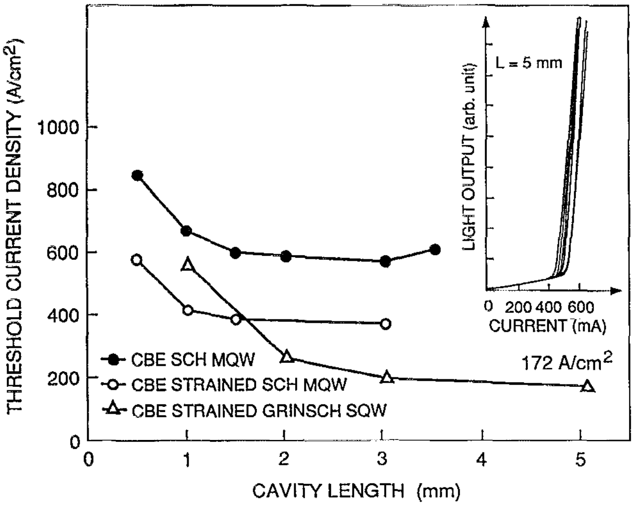

FIG. 1. Threshold current densities of CBE-grown unstrained 4 QW SCH lasers, strained-layer 4QW SCH lasers, and strained-layer 1 QW GRINSCH lasers plotted as a function of cavity length. The inset shows the light-current characteristics of six randomly picked 5-mm-long GRINSCH SQW lasers.

ferent cavity lengths ranging from 1 to 5 mm. Figure 1 shows the J_{th} as a function of the cavity length, and compared with CBE-grown 4QW SCH lasers and 4QW strained-layer SCH lasers. The inset shows the light-current characteristics of six 5-mm-long lasers checked in random from the wafer. Despite the very long cavity used, the thresholds were very uniform. For 4QW strained-layer SCH lasers having an $x = 0.65$ and $d = 5$ nm, the lowest J_{th} is 370 A/cm^2. The minimum J_{th} for the single quantum well GRINSCH laser at 1.59 μm wavelength is 170 A/cm^2 for a 5-mm-long cavity. This is the first report that long-wavelength InGaAsP injection lasers have a J_{th} below 200 A/cm^2. The monotonically decreasing J_{th} with increasing cavity length even up to as long as 5 mm for the single quantum well GRINSCH laser indicates that the waveguide loss is very low. This is confirmed by the plot of inverse external quantum efficiencies as a function of cavity length shown in Fig. 2. An internal waveguide loss α of 3.8 cm^{-1} was obtained, which is the same as that obtained by MOVPE-grown single quantum GRINSCH laser.[15] However, the present CBE-grown lasers have an internal quantum efficiency of 83% instead of 54% obtained by Thijs *et al.*[15] It is important to note that the α values obtained from both CBE- and MOVPE-grown single quantum GRINSCH lasers are substantially lower than those of MQW lasers ($\alpha \sim 15$ cm^{-1}). We also found that the lasing wavelength increased from 1.555 μm for a 1-mm-long cavity to 1.590 μm for a 5-mm-long cavity.

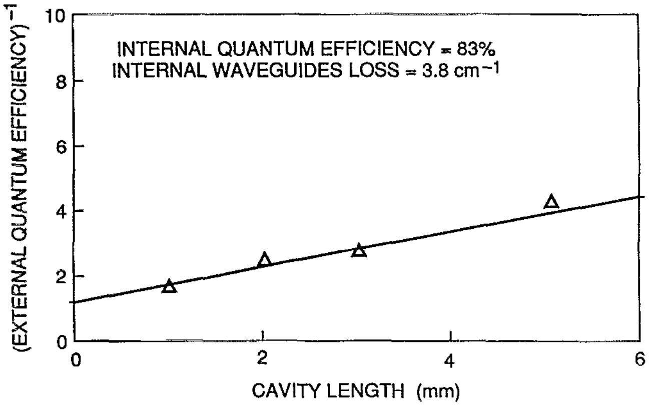

FIG. 2. Plot of inverse external quantum efficiencies as a function of cavity length for GRINSCH SQW lasers.

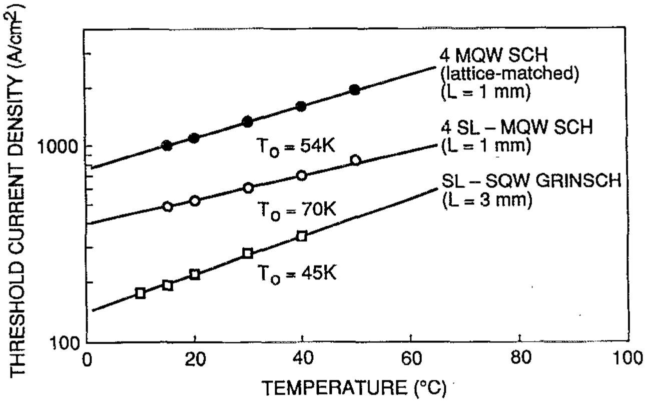

FIG. 3. Threshold current densities plotted as a function of heat-sink temperature for unstrained 4 QW SCH lasers, the strained-layer 4 QW SCH lasers, and the strained-layer GRINSCH SQW lasers.

Figure 3 shows the J_{th} as a function of heat-sink temperature for the three different types of QW lasers studied, the unstrained 4 QW SCH lasers, the strained-layer 4 QW SCH lasers, and the strained-layer 1QW GRINSCH lasers. The threshold-temperature dependence T_0 ranged from 45 to 70 K. Though the present data appear to suggest that the threshold-temperature dependence may be influenced by the number of quantum wells and the detailed layer designs of the active region, the highest T_0 possible is not expected to be large.

In summary, we have succeeded in preparing 1.5 μm wavelength strained-layer GRINSCH InGaAs/InGaAsP single QW injection lasers by CBE. These lasers have an extremely low threshold current density of 170 A/cm^2, internal quantum efficiency of 83%, and internal waveguide loss of 3.8 cm^{-1}. To the best of our knowledge, these results represent the best values obtained thus far from long-wavelength InGaAs/InGaAsP quantum well injection lasers grown by any techniques. For the first time, the J_{th} value of 170 A/cm^2 comes in the same range as those typically obtained for GaAs/AlGaAs GRINSCH lasers, though values as low as 50 A/cm^2 were obtained recently for InGaAs/AlGaAs strained-layer single quantum well lasers. Despite such rapid reductions in J_{th} of the long-wavelength InGaAs/InGaAsP quantum well lasers, the threshold-temperature dependence of these quantum well lasers remains rather poor.

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