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1.3 μm InGaAsP/InP multiquantum well buried heterostructure lasers grown by chemical-beam epitaxy

W. T. Tsang, F. S. Choa, R. A. Logan, T. Tanbun-Ek, M. C. Wu, Y. K. Chen, A. M. Sergent, and K. W. Wecht
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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High performance InGaAsP/InP multiquantum well (MQW) buried heterostructure lasers emitting around 1.3 μm were prepared for the first time by chemical-beam epitaxy. At 20 °C, continuous-wave (cw) threshold currents were 5–8 mA and quantum efficiencies were 0.35–0.45 mW/mA for 250 μm long lasers having one facet ~85% reflective coated. At 80 °C, the cw threshold currents remained low, 23 mA, quantum efficiency stayed high, 0.22 mW/mA, and output power of ~10 mW was achieved. cw power output as high as 125 mW was achieved with 750 μm long lasers having AR–HR (~5%–85%) coatings. Lasers with bulk active were also studied for comparison. Though they also have excellent device performance, in general, they are somewhat inferior to MQW lasers.

In the last decade there has been a tremendous effort worldwide in developing metalorganic vapor phase epitaxy (MOVPE) for the preparation of InGaAsP heterostructures for optoelectronic applications. In particular, very high performance 1.3–1.5 μm InGaAsP/InP double heterostructure, lattice-matched and strained multiquantum well (MQW) lasers[1–9] have been successfully prepared. At the beginning atmospheric-pressure MOVPE was employed.[8] However, at present, low-pressure (~100 Torr) MOVPE[1,6,7] is widely used due to the general belief that it offers the following advantages: (1) it reduces the formation of gas-phase parasitic reactions; (2) it improves the material uniformly over large areas; (3) it improves the abruptness of the heterointerfaces. On the other hand, the use of low-pressure MOVPE resulted in a significant increase in the consumption of chemicals, especially the hydrides. Chemical-beam epitaxy (CBE)[10,11] was developed as a further extension of the low-pressure MOVPE down to the pressure range of $\lesssim 10^{-4}$ Torr. In such a low pressure regime, the transport of the reactant chemicals becomes molecular beams. This completely eliminates gas-phase reactions, pyroysis of metalorganics, and flow patterns present in MOVPE, thus resulting in highly uniform material composition and thickness.[12,13] In addition, the predecomposition of the hydrides very significantly increases the efficiency of hydride usages. To date, very high quality materials, heterostructures, quantum wells, and state-of-the-art electronic and optoelectronic devices have been grown by CBE.[2,10–12] Recently, there has been a great interest in 1.3–1.5 μm InGaAsP/InP MQW lasers due to their expected importance in lightwave communications applications. To prepare CBE as a potential future epitaxial technique, it is important to investigate its capability for growing low threshold high performance MQW lasers.

1.3 μm InGaAsP/InP lasers with bulk actives have been prepared by CBE[14] recently with a threshold current density of ~2 kA/cm^2. In this letter, we present results on the performance of the last 1.3 μm InGaAsP/InP MQW buried heterostructure lasers grown by CBE. Unlike 1.5 μm MQW lasers in which the quantum wells are InGaAs and the barriers are quaternary, the preparation of 1.3 μm MQW lasers is more demanding because both the quantum wells and barriers are quaternaries. The CBE system used is a modified Riber CBE 32. The present system is completely vapor source equipped including the dopants. Diethylzinc (DEZn) and tetraethyltin (TESn) were used as the *p*-type and *n*-type dopant sources, respectively. They were injected together with the metalorganic trimethylindium (TMIn) and triethylgallium (TEGa) through a quartz injector (~70 °C) designed for high layer thickness uniformity.[10,12] Pure AsH_3 and PH_3 were thermally decomposed by passing through a low pressure cracker at ~980 °C. Hydrogen was used as the carrier gas. All flows were controlled using precision electronic mass flow meters. The epitaxial layers were grown on a (100) oriented sulphur-doped InP substrate. The separate confinement heterostructure (SCH) consists of InGaAsP quaternary (equivalent wavelength $\lambda = 1.15$ μm, thickness $d = 100$ nm) on either side of the quantum wells. In order to compare the performance of bulk-active and MQW lasers, two types of active layer structures were studied. In the bulk-active structure, two "wells" of InGaAsP ($\lambda = 1.32$ μm) of 37 nm each separated by a 22 nm InGaAsP ($\lambda = 1.15$ μm) barrier were grown. Such thick wells are not expected to exhibit quantum size effects at room temperature and hence, behave like a bulk active laser. In the MQW structure, eight quantum wells of InGaAsP ($\lambda = 1.32$ μm, $d = 9$ nm) were separated by InGaAsP barriers ($\lambda = 1.15$ μm $= 3.5$ nm). These laser wafers were further processed into buried heterostructure employing MOVPE regrowth of Fe-doped InP at 630 °C. Though CBE has been employed recently in regrowth by Gaihanou,[15] we have not perfected that yet.[16]

The inverse of quantum efficiency and continuous-wave cw threshold current of the 8 quantum well (QW) lasers as a function of cavity length is shown in Fig. 1. The internal quantum efficiency (η_i) and internal loss (α) were estimated to be ~67% and ~11.5 cm^{-1}, respectively. The

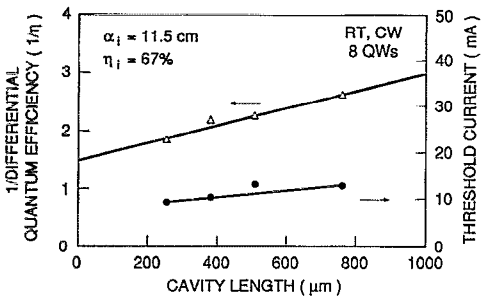

FIG. 1. The inverse of quantum efficiency and cw threshold current of the 8 QW lasers as a function of cavity length.

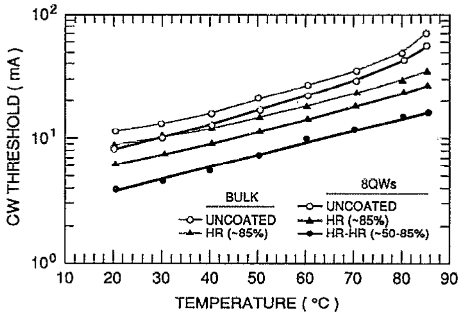

FIG. 3. The cw threshold currents for bulk active lasers and 8 QW lasers, facets uncoated, one side HR coated and both sides HR coated.

slightly lower η_i and higher α than those in broad area lasers measured previously[2] are possibly due to sidewall optical scattering losses in (BH) lasers. The threshold currents were as low as 6–10 and 12–15 mA for lasers having cavity lengths of 250 and 750 μm, respectively. To study the high temperature operation of these lasers, high reflectivity coatings ($\sim$85%) consisted of $\lambda/4$ stacks of evaporated SiO_2 and Si was applied to one facet of the 250-μm long lasers. The coated lasers have reduced threshold currents of 5–8 mA and show excellent slope efficiencies in the range of 0.35–0.45 nW/mA. Figure 2 shows the light-current characteristics of a typical MQW laser measured cw up to 85 °C. At 80 and 85 °C, the threshold currents are still as low as 23 and 26 mA, respectively, and a power output of 10 mW can still be obtained. Such excellent high temperature performance equals the best MOVPE grown 1.3 μm MQW lasers having similar structures.[17] Quantum efficiency drops from 0.4 to 0.2 mW/mA with temperature increased from 20 to 85 °C. In Fig. 3 we plot the cw threshold currents for bulk active lasers (uncoated and one facet $\sim$85% HR) and 8 QW lasers (uncoated, one facet $\sim$85% HR and both facets $\sim$50–85% HR) as a function of temperature. Both the bulk and MQW lasers have quite similar T_0, the characteristic-temperature-dependence coefficient of threshold current. T_0 in all cases is $\sim$45°. For the bulk active lasers (one facet HR coated) at 85 °C, the threshold current is still very low, 35 mA, but it is higher than the MQW lasers. The quantum efficiency drops from 0.36 to 0.15 mW/mA with temperature increased from 20 to 85 °C. High reflectivity coating reduces the threshold currents and pushes the high-temperture break-off point of a higher temperature. Both effects enhance the high-temperature performance of the lasers. Thus, the high temperature performance of the present MQW lasers is accomplished as a result of combined optimization of low threshold current and high quantum efficiency of the base (uncoated) laser diodes, the choice of cavity length and HR coating.

Figure 4 shows the light-current characteristics at room temperature for 250, 375, 500, and 750 μm long lasers. The lasers were AR–HR (estimated $\sim$5% and $\sim$85% reflectivities) coated. The cw threshold currents are less than 13 mA even for the 750 μm long diode. The maximum output power improved as the cavity length was increased. cw output power of 125 mW was obtained at an injection current of 500 mA in a 750 μm long laser.

In summary, we have demonstrated the first high quality InGaAsP/InP MQW buried heterostructure laser emitting at 1.3 μm grown by CBE. At 20 °C, cw threshold currents were 5–8 mA and quantum efficiencies were 0.35–0.45 mW/mA for 250 μm long lasers having one facet $\sim$85% reflective coated. At 80 °C, the cw threshold current remained low, 23 mA, quantum efficiency stayed high, 0.22 mW/mA, and output power of $\sim$10 mW was achieved. cw power output as high as 125 mW was achieved with 750-μm long lasers having AR–HR ($\sim$5%–85%) coatings. Such high temperature performance in the present lasers come from reduced threshold current, opti-

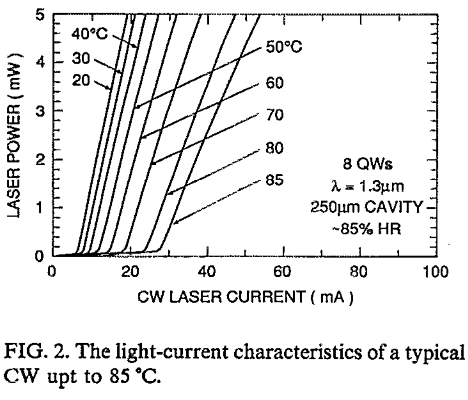

FIG. 2. The light-current characteristics of a typical 8 QW laser measured CW upt to 85 °C.

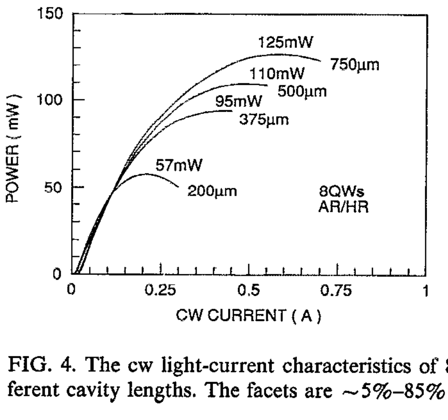

FIG. 4. The cw light-current characteristics of 8 QW lasers having different cavity lengths. The facets are $\sim$5%–85% AR–HR coated.

mization of facet reflectivity and cavity length. Lasers with bulk active were also studied for comparison. Though they also have excellent device performance, in general, they are somewhat inferior to MQW lasers.

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