Low threshold and high power output 1.5 m InGaAs/InGaAsP separate confinement multiple quantum well laser grown by chemical beam epitaxy

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We have demonstrated the first successful preparation of InGaAs/InGaAsP multiple quantum well (MQW) lasers grown by chemical beam epitaxy. The broad-area threshold current densities of standard (not graded index) separate confinement heterostructure (SCH) MQW lasers were as low as 860 and ~ 590 A/cm^2 for cavity lengths of 500 and 1500–3500 μm. Such values are similar to those obtained from MQW wafers employing the more advanced graded index SCH(GRIN-SCH) grown by metalorganic vapor phase epitaxy. Buried-heterostructure lasers also have similar threshold currents, i.e., 25–40 mA for 300–1500 long cavities. Pulsed and cw output power at 1.57 μm as high as 216 and 140 mW were obtained from 1-mm-long buried-heterostructure lasers having antireflection and high reflection coatings of $\sim 5\%$ and $\sim 85\%$. The layer thickness uniformity is better than $\pm 1\%$ across a 2-in.-diam wafer.

Quantum well lasers of GaAs/AlGaAs have been intensely investigated in the last few years.[1] The most commonly used structure is the graded index separate confinement heterostructure (GRIN-SCH).[2] This design results in highly efficient, extremely low threshold lasers, capable of very high power operation. Their internal loss is characteristically low. As a result, their external quantum efficiency and threshold current only weakly depend on the cavity length. The preparation of high quality quantum well lasers in the InGaAs/InP material has turned out to be quite different.[3,4] It is only until recently that sufficiently good quality InGaAs/InGaAsP multiple quantum well (MQW) lasers were prepared by metalorganic vapor phase epitaxy (MOVPE).[5-9] Yet, the performance improvement is not as dramatic as the GaAs/AlGaAs quantum well lasers. This is partly due to differences in the intrinsic properties of the two material systems, for example, the stronger Auger processes in the InGaAsP than in AlGaAs materials, and partly due to the demanding requirement of quantum well lasers for the very high perfection of materials and heterointerfaces.

Chemical beam epitaxy[10] (CBE) has been shown to produce very high quality InGaAs/InP quantum wells. Though quantum well lasers with InGaAs wells and InP barriers have also previously been prepared by CBE,[4,11] they did not show a reduction in the threshold current densities over double-heterostructure lasers with bulk active layers. This is mainly because the high InP barriers reduce the carrier injection efficiency of the quantum wells.[11]

In this letter, we report the first preparation of high quality InGaAs/InGaAsP multiple quantum well lasers having a standard separate confinement heterostructure (SCH) by CBE. The epitaxial layers were grown on a (100) oriented InP substrate using a modified Riber CBE32 and procedures described previously.[11,12] The active layer consisted of four 8-nm-thick lattice-matched $In_{0.53}Ga_{0.47}As$ quantum wells separated by three 17-nm-thick InGaAsP (lattice matched, 1.25 μm composition) barriers. The SCH InGaAsP waveguide layers on both sides of the active MQWs, each 40 nm thick, were of uniform composition (1.25 μm composition). The n-InP buffer layer was ~ 0.7 μm thick and the p-InP cladding layer was ~ 1.5 μm thick. Figure 1 shows a TEM micrograph of the SCH-MQW cross section. Sn and Be thermal beams were employed for n and p dopings, respectively. A p^+-InGaAsP (1.25 μm composition) top layer served for ohmic contact formation and etching mask during the mesa etching. At each layer interface, growth was interrupted for 1–5 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. The typical growth temperature was ~ 545 °C with the Be-doped InP grown at ~ 525 °C. The sample was further processed into buried-heterostructure (BH) lasers with regrowth done by metalorganic vapor phase epitaxy (MOVPE) using a ~ 3-μm-thick Fe-doped InP as the current blocking layer. The buried stripe width in this experiment was about 3 μm, somewhat wider than intended by mesa-etching time control.

For broad-area threshold current density J_{th} evaluation, 55-μm-wide oxide stripe lasers were fabricated with different cavity lengths ranging from 0.5 to 3.5 mm. Figure 2 shows the J_{th} as low as 860 A/cm^2 and ~ 590 A/cm^2 for 500 μm and 1500–3500 μm long cavities, respectively. Similar SCH laser grown by MOVPE with 4 QWs typically have threshold current densities of ~ 1.5 kA–2.0 kA/cm^2 for a 500-μm-long cavity.[13] For cavity lengths shorter than 2 mm, the CBE-grown standard SCH MQW lasers actually have similar J_{th} as those GRIN-SCH MQW lasers grown by MOVPE.[9] However, it appears that for very long cavity lasers, the GRIN-SCH lasers have a lower threshold. This is probably due to the fact that the GRIN-SCH lasers have lower waveguide losses.

This is borne out by the result shown in Fig. 3(a), where the inverse of the internal quantum efficiency is plotted as a function of the cavity length for CBE-SCH-MQW-BH lasers. Such an analysis gives the internal loss

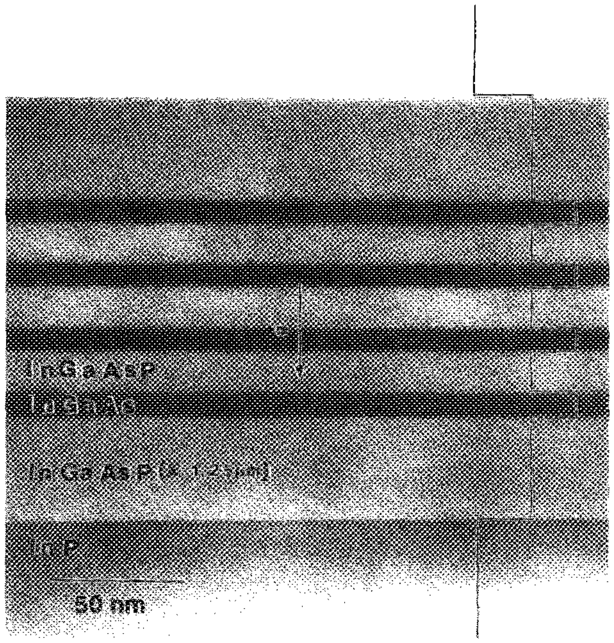

FIG. 1. Transmission electron microscope photograph of the cross section of a four quantum well lattice-matched InGaAs/InGaAsP standard (not graded index) SCH laser.

α_i and the internal efficiency η_i. Through $\eta_i \sim 80\%$ is similar to that obtained for MOVPE-grown GRIN-SCH lasers, the waveguide absorption loss, $\alpha_i \sim 18\ \mathrm{cm}^{-1}$, is somewhat higher than that obtained for MOVPE GRIN-SCH lasers ($\sim 15\ \mathrm{cm}^{-1}$).[13,14] It is expected that by employing the more advanced GRIN-SCH in the future, further reduction in threshold current density may be possible with CBE growth.

Figure 3(b) shows the cw threshold currents for CBE-SCH-MQW-BH lasers as a function of cavity length. Plotted in the same figure are the results from MOVPE-grown strained MQW GRIN-SCH[15] and standard SCH lasers.[16] Consistent with broad-area results, the present CBE BH

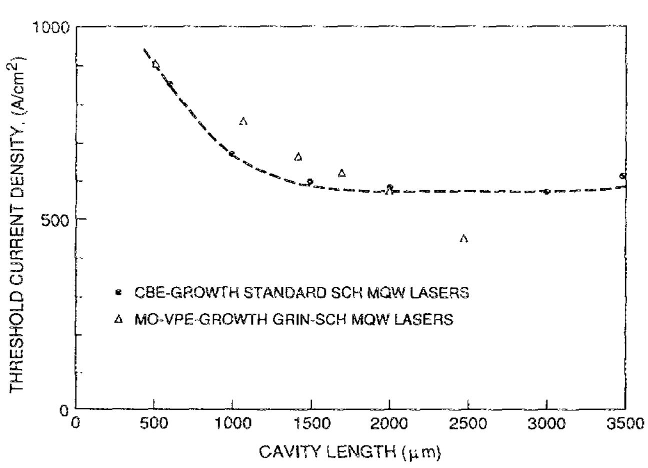

FIG. 2. Broad-area threshold current density of 55-μm-wide oxide stripe lasers as a function of cavity length for both CBE-grown standard SCH and MOVPE-grown GRIN-SCH lasers.

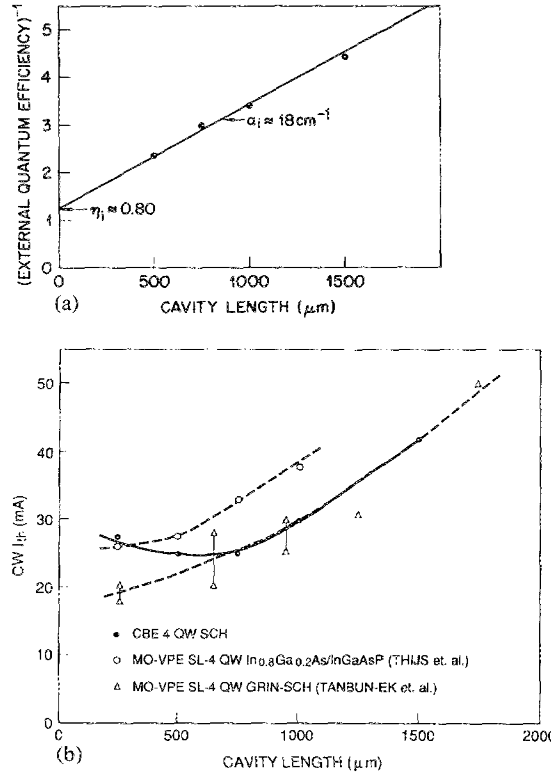

FIG. 3. (a) Inverse of external quantum efficiency of buried-heterostructure MQW SCH lasers as a function of cavity length. (b) Threshold currents as a function of cavity lengths for CBE-grown standard SCH MQW BH lasers, MOVPE-grown strained SCH lasers (Ref. 16), and MOVPE-grown strained GRIN-SCH lasers (Ref. 15).

lasers also have similar threshold currents as those GRIN-SCH lasers and somewhat lower than those of standard SCH lasers grown by MOVPE. Threshold currents of 25–40 mA were obtained for 0.3–1.5 mm long cavity lasers. With narrower active stripe widths, some further reduction may be possible. It should be noted that in this comparison the current leakage across the regrown layer is minimized in all three cases.

The pulsed and cw light output versus current of a 1-mm-long cavity CBE-SCH-MQW-BH laser is shown in Fig. 4. The facet reflectivity at the front and rear facets were about 5% and 85%, respectively. Pulsed output power of 216 mW/front facet was obtained. Under cw operation, 140 mW/front facet was obtained. This is believed to be limited by heat sinking. With no AR HR coating, cw power of 125 mW/facet was also measured. The lasting wavelength was at $\sim 1.57\ \mu$m. These values are similar to those obtained from 1.55 μm MQW-BH lasers grown by MOVPE. However, at 1.48 μm cw output power as high as 206 mW has been obtained recently from MOVPE-grown MQW BH lasers.[15]

In CBE, due to the absence of flow patterns and the ability to tailor the flux distribution of the metalorganic beam,[10] very uniform layer thicknesses across a large area can be obtained. Figure 5 shows the thickness uniformity across a 2-in.-diam laser wafer measured in two perpendicular directions. The layer thickness is measured by employing the laser interference technique. In Fig. 5 the combined thickness of the top p^+-InGaAsP and p-InP layers was

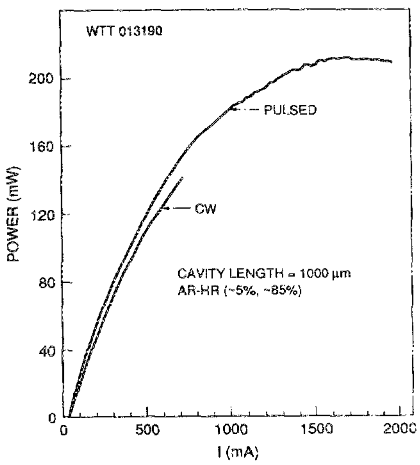

FIG. 4. Pulsed and cw output power vs current for a SCH MQW BH laser with AR-HR coating of ~5% and ~85%.

plotted. The thickness uniformity is better than ±1% across the 2-in.-diam wafer.

In summary, we have demonstrated the first successful preparation of InGaAs/InGaAsP MQW lasers by CBE.

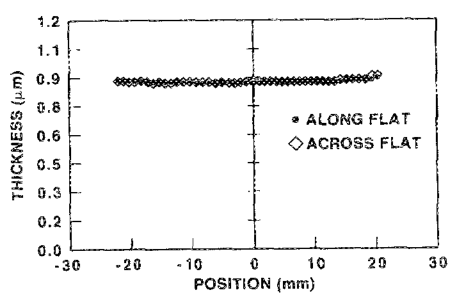

FIG. 5. Combined layer thickness of the top p^+-InGaAsP and p-InP layers of a 2-in-diam CBE-grown laser wafer measured in two perpendicular directions by employing the laser interference technique.

The broad-area threshold current densities of standard SCH lasers were as low as 860 and ~590 A/cm^2 for cavity lengths of 500 and 1500–3500 μm. Such values are similar to those obtained from MOVPE-grown MQW wafers but employing the more advanced GRIN-SCH structure. Buried-heterostructure lasers also have similar threshold currents, i.e., 25–40 mA for 0.3–1.5 mm long cavities. Pulsed and cw output power as high as 216 mW and 140 mW were obtained from the front face of AR HR (~5%, ~85%) coated lasers with a 1-mm-long cavity. The layer thickness uniformity is better than ±1% across a 2-in.-diam wafer.

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