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Citation: Applied Physics Letters **61**, 755 (1992); doi: 10.1063/1.107788
View online: http://dx.doi.org/10.1063/1.107788
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Low-threshold InGaAs strained-layer quantum well lasers ($\lambda = 0.98\ \mu$m) with GaInP cladding layers prepared by chemical beam epitaxy

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(Received 23 March 1992; accepted for publication 8 June 1992)

We report on the InGaAs/GaAs/GaInP strained-layer quantum well (QW) lasers grown by chemical beam epitaxy (CBE). The single QW broad-area layers have a very low threshold current density of 70 A/cm^2, which is among the lowest value reported for InGaAs/GaAs/GaInP lasers. Ridge-waveguide lasers emitting at 0.98 μm have a continuous wave (cw) threshold of 7.8 mA for a 500-μm-long cavity and a differential quantum efficiency as high as 0.9 mW/mA. Internal quantum efficiency of 0.95 and internal waveguide losses of 2.5 cm^{-1} were obtained. Linear cw output power of 100 mW was obtained. These results demonstrate that CBE is capable of growing 0.98 μm InGaAs strained-layer QW lasers having performance similar to the best prepared by other epitaxial growth techniques.

Strained InGaAs/AlGaAs quantum well (QW) lasers are currently of great interest[1-9] because the emission wavelength can be extended to ~1.1 μm beyond the long-wavelength limit of ~0.89 μm for GaAs/AlGaAs lasers. Such extension of wavelength by the addition of In to the GaAs active layer of GaAs/AlGaAs lasers was first proposed and demonstrated in 1981 by Tsang.[10] The recent importance of the InGaAs/AlGaAs lasers operating at 0.98 μm is its suitability as the pumping source for the erbium-doped fiber optical amplifiers.[8,9] They yield a lower noise figure[8] and higher gain coefficient[9] than the 1.48 μm InGaAsP/InP pump lasers. In addition, the InGaAs/AlGaAs strained QW lasers have lower threshold current, higher slope efficiency, and less temperature dependence. All these are particularly important for lowering the power dissipation of the pump design. Previously, AlGaAs is commonly used for cladding layers. Recently, $Ga_{0.51}In_{0.49}P$ lattice-matched to GaAs was introduced as a substitution for the AlGaAs cladding layers.[11-13] They have been grown by metalorganic vapor phase epitaxy (MOVPE)[11,12] and gas-source molecular beam epitaxy (GSMBE).[13] $Ga_{0.51}In_{0.49}P$ is of interest in InGaAs lasers because of recent reports suggesting its superior resistance over AlGaAs alloys to rapid degradation by dark line defect propagation[11] and catastrophic mirror damage.[14] In addition, the aluminum-free systems lend themselves more readily to device fabrication by selective etching and epitaxial regrowth or mass transport.[12] In this letter, we report on the first InGaAs/GaAs strained-layer QW lasers using $Ga_{0.51}In_{0.49}P$ cladding layers grown by chemical beam epitaxy (CBE).[15,16]

The InGaAs/GaAs/GaInP QW lasers were grown on (100) *n*-GaAs substrates by CBE using triethylgallium (TEGa), trimethylindium (TMIn), and thermally decomposed phosphine (PH_3). Diethylzinc (DEZn) and hydrogen sulfide (H_2S) were used as the *p*-type and *n*-type doping sources, respectively. The substrate growth temperature was ~540 °C for all the layers except the *p*-GaInP and p^+-GaAs which were grown at ~510 °C. Lattice match of GaInP within $\Delta a/a \lesssim 5\times10^{-4}$ was relatively easily obtained. However, we found that the morphology was very sensitive to substrate growth temperature. This imposes a very stringent requirement on the reproducible control of growth temperature and temperature uniformity across the wafer. Details of the growth conditions and the properties of GaInP will be published elsewhere.

The layer structure of the InGaAs/GaAs/GaInP after fabricating into a ridge-waveguide structure is shown in Fig. 1. A 0.2 μm n^+-GaAs buffer layer was grown first. A separate confinement heterostructure (SCH) was used here to provide confinement of electrical carriers as well as optical field. The active region consists of one, two or three 70 Å-thick $In_{0.2}Ga_{0.8}As$ quantum wells and 220 Å-thick GaAs barriers, which produce a lasing wavelength of 980 nm. The active region is sandwiched between two 1000 Å-thick GaAs separate confinement layers. The active and the SCH region are cladded by $Ga_{0.51}In_{0.49}P$ layers of ~1.35 μm thickness. To facilitate the fabrication of ridge waveguide lasers, a thin GaAs stop-etch layer is inserted in the upper GaInP cladding layer. Ridge waveguides of 4 μm width were formed by selective wet chemical etching, which removed the GaInP material above the stop-etch layer. Then the etched wafer was covered by Si_3N_4 and a self-aligned process was used to define the *p*-contact opening on top of the ridge. Standard metallization and cleaving

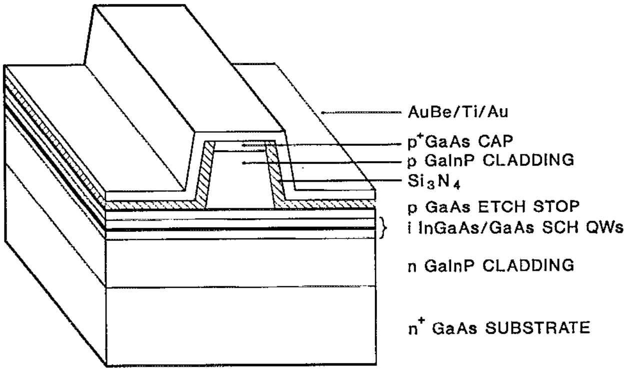

FIG. 1. The schematic of the self-aligned ridge-waveguide InGaAs/GaAs quantum well laser with lattice-matched GaInP cladding layers.

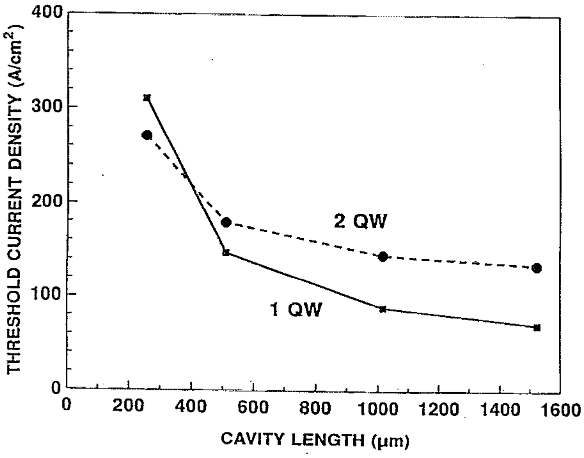

FIG. 2. The cavity length dependence of the threshold current densities J_{th} for broad-area lasers having a single and two quantum wells.

processes were used to finish the fabrication.

Figure 2 shows the cavity length dependence of the threshold current densities J_{th} for broad-area lasers having a single and two quantum wells. A very low J_{th} of 70 A/cm^2 was obtained for a 1500-μm long single QW laser. Such J_{th} is among the lowest reported for InGaAs/GaAs/GaInP lasers. For comparison, a J_{th} of 177 and 85 A/cm^2 were obtained by GSMBE[13] and MOVPE,[12] respectively. In comparison to devices with AlGaAs cladding layers, the present J_{th} is among the best values of 65 A/cm^2 obtained by MOVPE[17] and ~50 A/cm^2 by MBE.[18,19]

The ridge waveguide lasers have very low continuous wave (cw) threshold currents: 7.8 mA for 500 μm-long cavity and 10 mA for 750 μm-long cavity. Such values are lower than those obtained from similar laser structures grown by GSMBE.[13] A typical cw light-current characteristic for a 750 μm-long laser with both facets as-cleaved is shown in Fig. 3. External differential quantum efficiency as high as 0.9 mW/mA was obtained for 250 μm-long lasers. The inset shows the lasing spectrum at 0.98 μm. 500-μm long lasers were high-reflective (~85%)/antireflective (~5%) coated. They emitted linear cw output powers up to 100 mW. Higher output power was possible but higher transverse mode set in. Figure 4 shows the cw threshold currents and the inverse of external quantum efficiency for single QW ridge waveguide lasers as a function of cavity lengths. From the slope of inverse quantum efficiency vs cavity length, a very low internal waveguide loss α_i of 2.5 cm^{-1} and internal quantum efficiency η_i of 0.95 were measured. The present value of α_i is close to the lowest reported. A α_i of 5 and 9 cm^{-1} were previously reported for MOVPE-grown InGaAs/GaAs/AlGaAs lasers[17] and GSMBE-grown InGaAs/GaAs/GaInP lasers,[13] respectively. Figure 5 shows the temperature dependence of cw threshold currents and external quantum efficiencies of a 750-μm long ridge waveguide laser as a function of heat-sink temperature. The diode was bonded p side up on copper heat-sink. A threshold-temperature dependence coefficient, T_0 of 90 K was measured. At 100 °C the external quantum efficiency stayed at ~0.8 mW/mA.

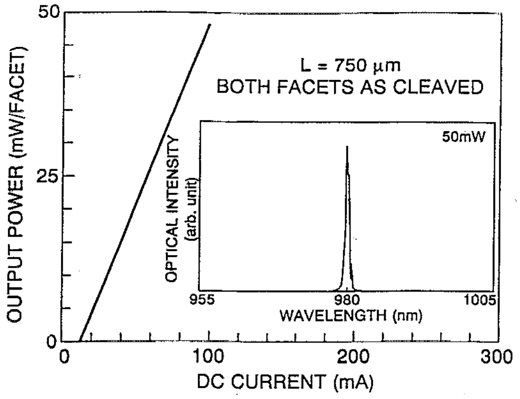

FIG. 3. A typical cw light-current characteristic for a 750 μm-long single QW ridge waveguide (4 μm wide) laser with both facets as-cleaved. The inset shows the lasing spectrum.

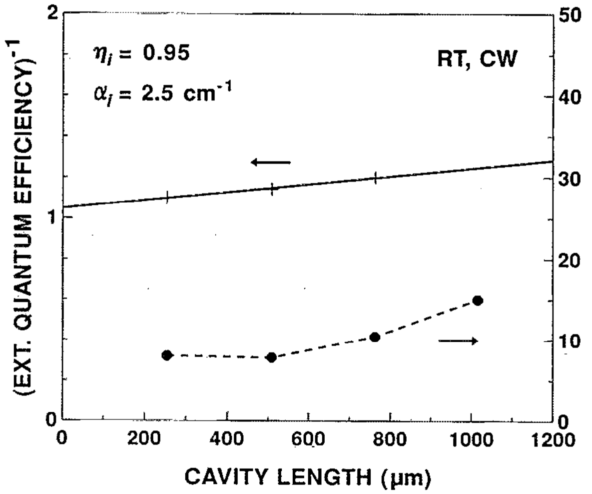

FIG. 4. The inverse external differential quantum efficiency and the threshold current vs the cavity length for single QW ridge waveguide lasers. The extrapolated internal quantum efficiency is 95% and the internal waveguide loss is 2.5 cm^{-1}.

In summary, we reported on the InGaAs/GaAs/

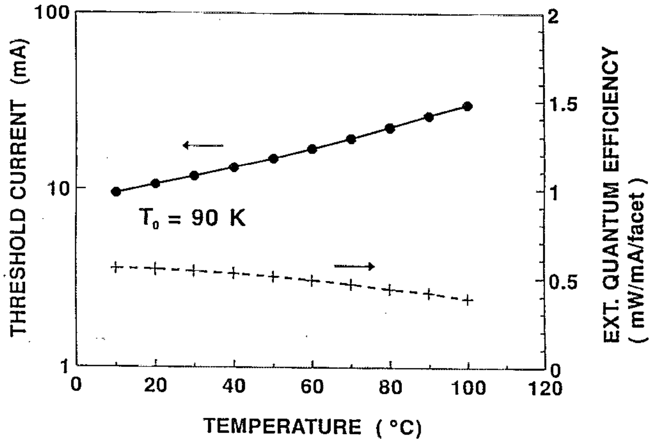

FIG. 5. The temperature dependence of the cw threshold currents and external quantum efficiencies of a 750 μm-long single quantum well ridge waveguide laser.

GaInP strained-layer quantum well lasers grown by CBE. The single QW broad-area lasers have a very low threshold current density of 70 A/cm^2, among the lowest value reported for InGaAs/GaAs/GaInP lasers. Ridge-waveguide lasers emitting at 0.98 μm have a cw threshold of 7.8 mA for a 500 μm-long cavity and a differential quantum efficiency as high as 0.9 mW/mA. Internal quantum efficiency of 0.95 and internal waveguide losses of 2.5 cm^{-1} were obtained. Linear cw output power of 100 mW was obtained. These results demonstrate that CBE is capable of growing 0.98 μm InGaAs strained-layer QW lasers having performance similar to the best prepared by other epitaxial growth techniques.

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