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1.5 μm wavelength InGaAs/InGaAsP distributed feedback multi-quantum-well lasers grown by chemical beam epitaxy

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We demonstrated the first successful growth of 1.5 μm strained-layer InGaAs/InGaAsP multi-quantum-well (MQW) distributed feedback (DFB) lasers by chemical beam epitaxy (CBE). In these DFB wafers, a quaternary grating is placed at the bottom of the MQW stack with an InP spacer layer. Studies by transmission electron microscopy show that defect-free InP regrowth was achieved with no mass transport needed over the grating corrugations before regrowth. With CBE regrowth the shapes of the gratings were well preserved. The InP overlayer also very effectively smoothed out the quaternary surface corrugations resulting in very flat MQW structures. Buried-heterostructure 6-QW DFB lasers (250 μm long and as-cleaved) operated at 1.55 μm with cw threshold currents 10–15 mA and slope efficiencies up to 0.35 mW/mA (both facets). Side-mode suppression ratios (SMSR) as high as 49 dB was obtained. The laser operated in the same DFB mode with SMSR staying above 40 dB from threshold and throughout the entire current range even at high temperatures (70 °C checked).

Multi-quantum-well (MQW) distributed feedback (DFB) lasers in the 1.3–1.55 μm wavelength range employing the InGaAsP/InP materials have been investigated very intensively.[1] This is because they offer very important performance advantages over bulk-active DFB lasers, such as reduced frequency chirping under high-speed direct modulation, narrower linewidth, larger TE/TM mode discrimination, and lower threshold currents, etc. To date, metalorganic vapor phase epitaxy (MOVPE) is almost the exclusive epitaxial growth technique employed in their preparation.[2] Liquid-phase epitaxy is incapable of growing the thin layer structures needed for the MQW lasers. Similarly, the fast growth rate of the hydride VPE tends to render the growth of the MQW thin layers not easily controllable due to the short growth times needed. Recently, we have demonstrated that chemical beam epitaxy (CBE)[3,4] is capable of growing 1.5 μm wavelength strained-layer graded-index separate-confinement heterostructure (GRINSCH)QW lasers[5] having extremely low threshold current density of 170 A/cm^2, internal quantum efficiency of 83%, and internal waveguide loss of 3.8 cm^{-1}. However, the preparation by CBE of DFB lasers remains a great challenge and of technological importance because *defect-free* growth over corrugated surface (grating) proves to be a nontrivial process even for MOVPE. Technologically, CBE is well suited for the growth of DFB laser wafers because of its high degree of precise thickness and composition control, and large-area uniformity. Such control and uniformity are essential in producing DFB lasers with uniform device performance such as lasing wavelength and optical coupling.

In this letter, we demonstrate the first successful growth of 1.5 μm wavelength strained-layer InGaAs/InGaAsP MQW DFB lasers by CBE. Unlike the common practice in designing the DFB layer structures, an InGaAsP quaternary grating (band-gap wavelength $\lambda = 1.25$, for convenience it will be referred to as $Q_{1.25}$) is placed at the bottom of the MQW stack with an InP spacer layer. The advantages of this scheme will be discussed later.

Figure 1(a) shows a schematic diagram of the laser structure together with a cross-sectional TEM photograph in Fig. 1(b). To fabricate this a uniform *n*-type $Q_{1.25}$ layer of the desired thickness (in this sample, 62 nm was used) for grating fabrication was grown over a 2-in.-diam (100)-oriented *n*-InP substrate. It has been shown previously that the present CBE system is capable of producing layers having a thickness uniformity of $\lesssim \pm 1\%$ and a photoluminescence (PL) peak wavelength uniformity of $\lesssim \pm 5$ nm (as good as ± 1.5 nm).[6,7] First-order gratings were prepared by standard holographic techniques and wet etching and had an amplitude of $\sim$22 nm as shown in Fig. 1(b). When desired, deeper gratings can be produced by longer etching times. By growing the appropriate $Q_{1.25}$ thickness and controlling the etching times, quaternary gratings completely buried in InP material can be obtained with the desired pitch ratio. At the same time, the depth of the grating is automatically given by the thickness of the $Q_{1.25}$ layer. After cleaning, the sample was reintroduced into the CBE system for MQW laser regrowth. The substrate was heated up to $\sim$545 °C under phosphorus overpressure from precracked phosphine (PH_3). Under such low-temperature conditions, no grating erosion was ever observed. The detailed shape of the grating was well preserved as shown by the TEM photograph in Fig. 1(b). An *n*-type InP spacer layer of the desired thickness (68 nm in the present laser) for controlling the coupling constant κ was grown. This was then followed by a standard strained-layer six-QW separate-confinement heterostructure. The strained-layer $In_xGa_{1-x}As$ QWs ($x \sim 0.65$) and $Q_{1.25}$ barriers were 4.8 and 25 nm, respectively. The $Q_{1.25}$ waveguide layer on each side of the MQW stack was 75 nm. The structure was grown with all vapor sources including the *n*- and *p*-type dopings. Diethylzinc and tetraethyltin were used as the

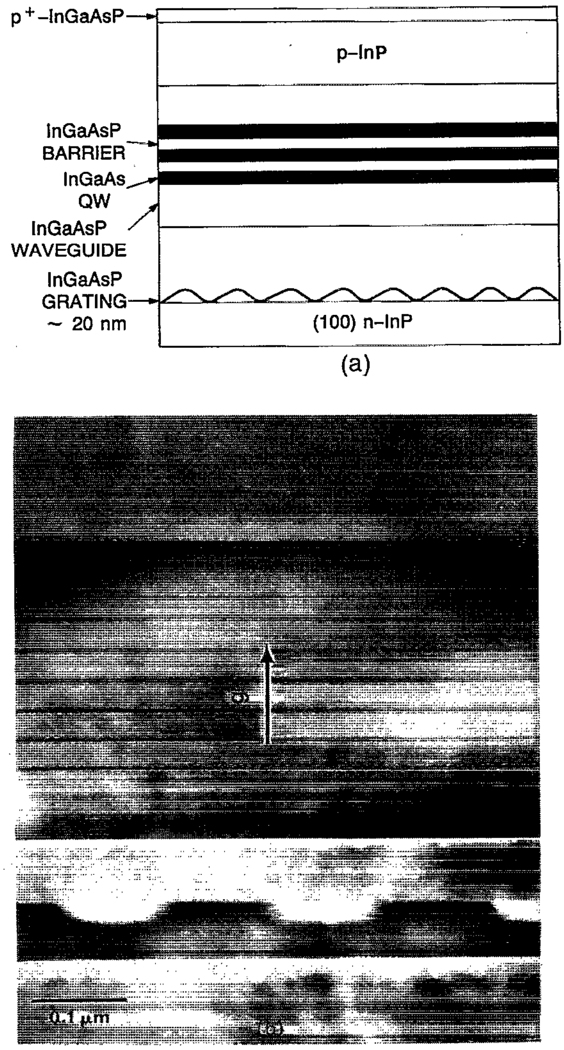

FIG. 1. (a) A schematic diagram of the MQW DFB laser structure with a bottom quaternary grating. (b) A cross-sectional TEM photograph of a CBE-grown strained-layer six-QW DFB laser wafer. Defect-free InP overgrowth was achieved with no grating erosion.

p-type and *n*-type doping sources, respectively. Finally, buried-heterostructure lasers were formed by MOVPE regrowth with semi-insulating iron-doped InP. Occasionally, we found that there are some lines in the $Q_{1.25}$ layers as revealed by the TEM photograph. These are real. Their cause is unknown at present. We believe these are due to sudden composition changes as a result of bubblings in the triethylgallium bubbler.

In MOVPE regrowth over grating, especially over InP gratings on the substrate surface, extreme care is needed in order to avoid serious grating erosion[2] during the substrate heat up to ~630 °C. On the other hand, it was found that a controlled amount of mass transport is needed for the successful growth of dislocation-free epilayer structure over the gratings. Since the exact amount of mass transport is rather difficult to control reproducibly, the resulting grating shape and depth can affect the coupling constant κ in an unpredictable manner. Yet, it has been shown that the device characteristics, e.g., spectral linewidths, harmonic distortions, and relative intensity noise, etc., depend sensitively on the coupling constant.[8] An examination of the CBE-grown DFB wafers using TEM shows no mass transport of the quaternary grating profile. More importantly, no dislocation defects were observed, and the QW multilayers were extremely flat. An example is shown by the TEM photograph in Fig. 1(b).

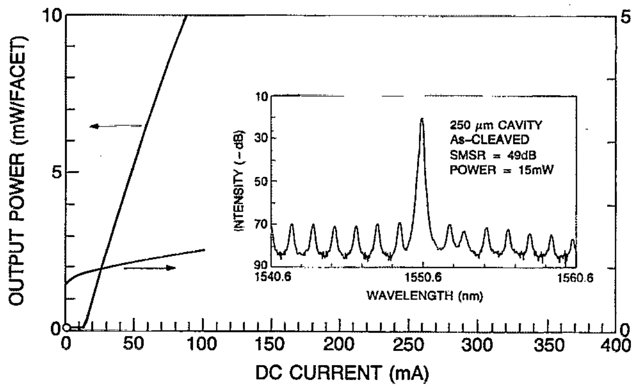

FIG. 2. Light-current and current-voltage characteristics of a typical CBE-grown buried-heterostructure MQW DFB laser. The inset shows the spectrum obtained at an output power of ~15 mW/facet. A SMSR of 48.5 dB was measured.

In the case of InP substrate grating, $Q_{1.1}$ is usually grown first. This is dictated by the waveguide design requirement and the more tolerance in lattice matching of $Q_{1.1}$ as it is relatively close to the InP material. As a consequence, the refractive-index difference between the InP grating and the $Q_{1.1}$ overlayer is small. There is no such limitation when quaternary grating is employed. Further, the growth of quaternary over corrugated surface exposing different crystal planes may result in locally mismatched and nonuniform materials. Severe cases lead to the generation of dislocation defects. This may explain why mass transport is needed for dislocation-free growth of quaternaries over InP gratings. On the other hand, there is no such issue when InP is grown over quaternary gratings, and InP smooths out the corrugation much faster than quaternary overlayers [see Fig. 1(b)].

The resulting DFB lasers (250-μm-long cavity and both facets as-cleaved) operated at 1.55 μm with cw

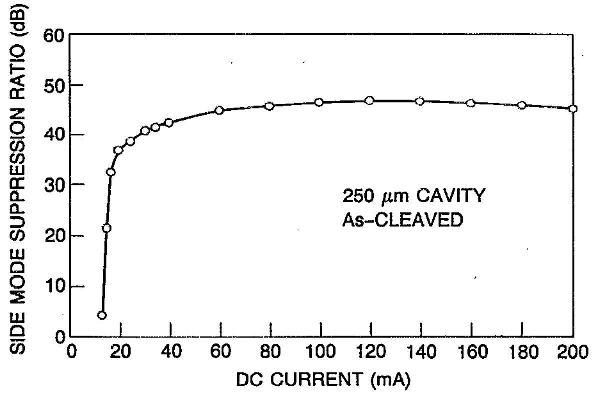

FIG. 3. SMSR as a function of injection current.

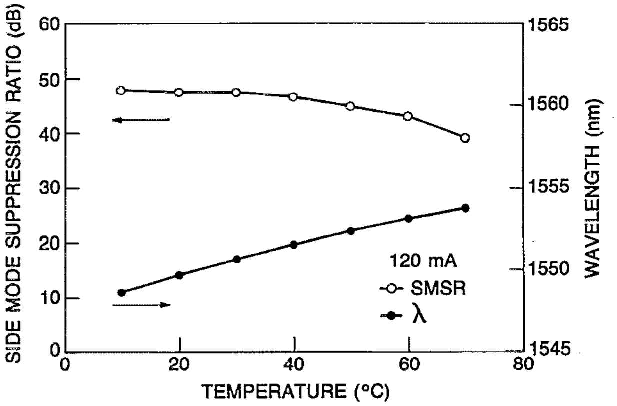

FIG. 4. SMSR and lasing wavelength were measured as a function of temperature keeping the operating current constant at 120 mA.

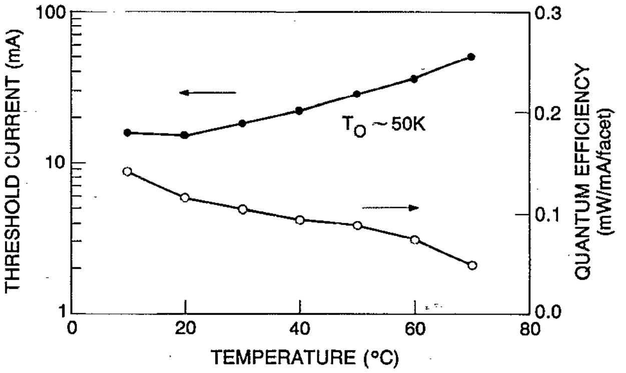

FIG. 5. cw threshold currents and slope efficiencies were plotted as a function of heat-sink temperature.

threshold currents 10–15 mA and slope efficiencies up to 0.35 mW/mA (both facets). Side-mode suppression ratios (SMSR) as high as 49 dB have been obtained in as-cleaved lasers without facet coatings. These performance values are among the best DFB lasers grown by other techniques.[1,2] Typical light-current and current-voltage characteristics are shown in Fig. 2. The inset shows the spectrum obtained at output power of ~15 mW/facet. A SMSR of 48.5 dB was obtained. The laser operated in the same DFB mode with SMSR staying above 40 dB starting right above threshold and throughout the entire current range as shown in Fig. 3. No mode jumps were observed in the threshold crossing. We also investigated the device performance as a function of heat-sink temperature. Keeping the operating current constant, the SMSR and lasing wavelength were measured as a function of temperature. The DFB laser stayed stably in the same DFB mode and with high SMSR even at high temperatures (70 °C checked here). Figure 4 shows an example with the operating current maintained at 120 mA. SMSR decreased from 48 dB at 10 °C to 40 dB at 70 °C, while the lasing wavelength increased at a rate of 0.083 nm/°C. In Fig. 5 we show the cw threshold currents and slope efficiencies as a function of temperature. The threshold temperature-dependence coefficient T_0 is ~50 K. For actual system applications, AR/HR coatings are needed in order to increase the slope efficiency and the output power from the output facet. It will also increase the high temperature operation range of the diode.

In summary, we have demonstrated the first successful growth of 1.5 μm strained-layer InGaAs/InGaAsP MQW DFB lasers by CBE. In these DFB wafers, a quaternary grating is placed at the bottom of the MQW stack with an InP spacer layer. Defect-free InP regrowth was achieved with no mass transport needed over the grating corrugations before growth. With CBE regrowth no grating erosion was observed. The shapes of the gratings were well preserved. The InP overlayer also very effectively smoothed out the quaternary surface corrugations resulting in very flat MQW structures. Buried-heterostructure six-QW DFB lasers (250 μm long and as-cleaved) operated at 1.55 μm with cw threshold currents 10–15 mA and slope efficiencies up to 0.35 mW/mA (both facets). SMSR as high as 49 dB was obtained. The laser operated in the same DFB mode with SMSR stayed above 40 dB from threshold and throughout the entire current range even at high temperatures (70 °C checked).

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