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Reproducible growth of narrow linewidth multiple quantum well graded index separate confinement distributed feedback (MQW-GRIN-SCH-DFB) lasers by MOVPE

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We describe reproducible growth of multiple quantum well graded index separate confinement distributed feedback (MQW-GRIN-SCH-DFB) lasers by atmospheric pressure metalorganic vapor phase epitaxy (MOVPE). Epitaxial layers were grown directly on a first order grating prepared on a (100) n-InP substrate. The gratings were preserved by introducing a suitable mixture of AsH_3 and PH_3 into the reactor. The quality of epitaxial layers grown on preserved gratings was found to improve by deposition of a very thin quaternary layer (7 nm thick) at low temperature (500°C), before the growth of the waveguide and subsequent graded index layers at the normal growth temperature (625°C). With the cavity length varied from 0.5 to 2 mm, the corresponding threshold currents were 22 and 100 mA, respectively. A remarkable improvement in both laser linewidth and output power was observed with devices as long as 2–3 mm. With 2 mm long device we observed linewidth as narrow as 600 kHz at a power output of 35 mW.

1. Introduction

Very narrow linewidth semiconductor lasers are important for coherent optical communication systems [1] using heterodyne or homodyne detection which results in improved receiver sensitivity as compared to direct envelope detection. Recent progress in crystal growth by metalorganic vapor phase epitaxy (MOVPE) has been the major impetus in the realization of more sophisticated device structures such as InGaAs/InP quantum well lasers. Many improvements in characteristics were achieved by factors such as low internal loss of the waveguide layers and the inherent higher internal quantum efficiency of a graded index separate confinement single or multiple quantum well lasers. These lasers are then a very attractive structure [2–5] to be incorporated into distributed feedback lasers. Moreover, the low optical confinement inside the quantum well active layers results in more efficient interaction between the light and the gratings and only very shallow gratings are needed in the DFB structure. These shallow gratings, i.e. small coupling coefficient, also result in an improvement in quantum efficiency as well as output power while allowing a single mode operation with a very narrow linewidth. Here we report a detailed growth as well as device characteristics of the graded index separate confinement distributed feedback lasers emitting at 1.52 μm.

2. MOVPE growth

The MOVPE growth was performed at atmospheric pressure on (100) n-InP substrate containing first order gratings. The preservation of the gratings during the heat up process will be described in detail in the next section. The epitaxial layers were grown in a horizontal reactor with an automated vent–run pressure balancing to minimize any transient pressure which might occur during the gas switching sequences. Purified hydrogen was used as carrier gas with a total flow of 5 l/min. The constituents are 5% AsH_3, 20% PH_3 diluted in H_2, trimethylindium (TMIn) and trimethylgallium (TMGa), with the latter two held at 30.0 and −15.0°C, respectively. The dopant sources were 200 ppm H_2S in H_2 and diethylzinc

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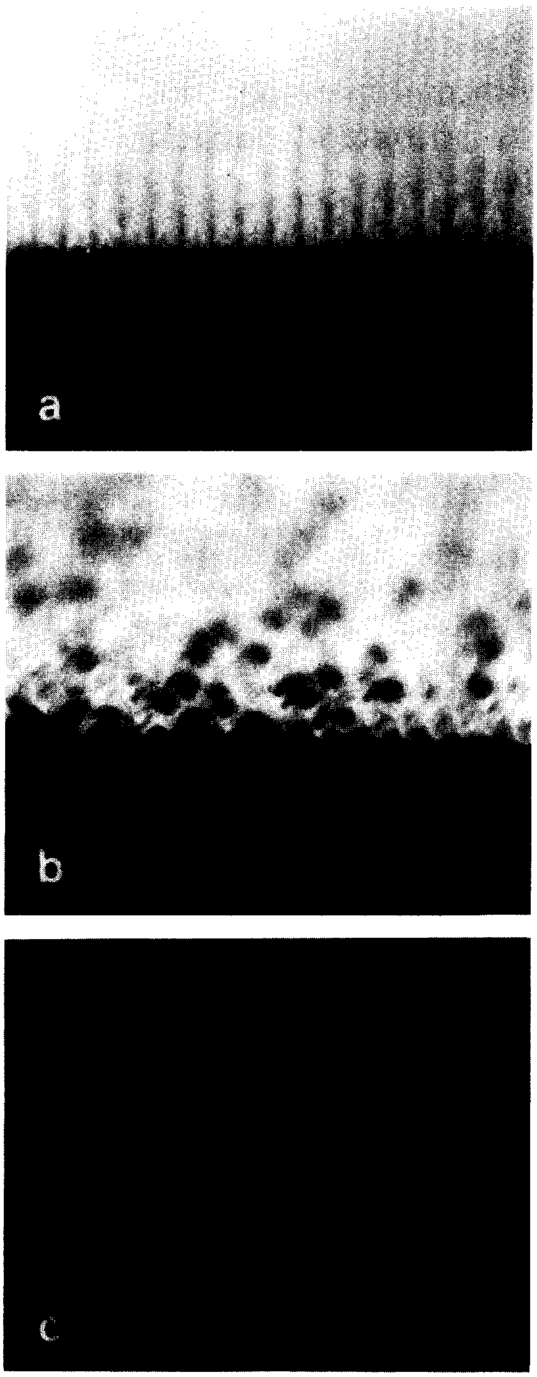

Fig. 1. Gratings on (100) n-InP substrate before heat treatment (a), after heat treatment (b), and after heat treatment with proper protection (c).

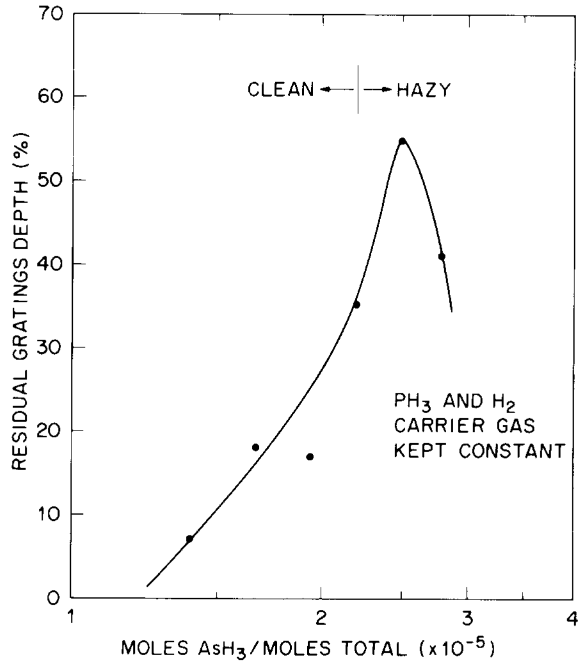

Fig. 2. Plot of residual gratings depth after heat treatment as a function of AsH_3 flow in the reactor.

(DEZn) for n-type and p-type doping, respectively. The growth temperature of all the epitaxial layers was at 625°C, except for the very first quaternary layer grown to protect the gratings which was deposited at 500°C. Typical growth rates are 1.5 nm/s for InGaAs and 1 nm/s for InP. The double crystal X-ray diffractometer measurements have shown that the lattice mismatch of all the layers including InGaAs and InGaAsP having bandgap, and the corresponding wavelength, ranging from 0.99 to 1.60 μm, are typically less than 3×10^{-4} and the FWHM of the (400) X-ray peak of the films are typically in the range of 25–50 arc sec.

3. Grating preservation

The gratings were formed by conventional holographic photolithography and chemical etching on (100) n-InP substrate. The interference grating was set to parallel the $(01\bar{1})$ direction. Fig. 1a shows the grating before any heat treatment. Typical grating depth is 100–150 nm and the period

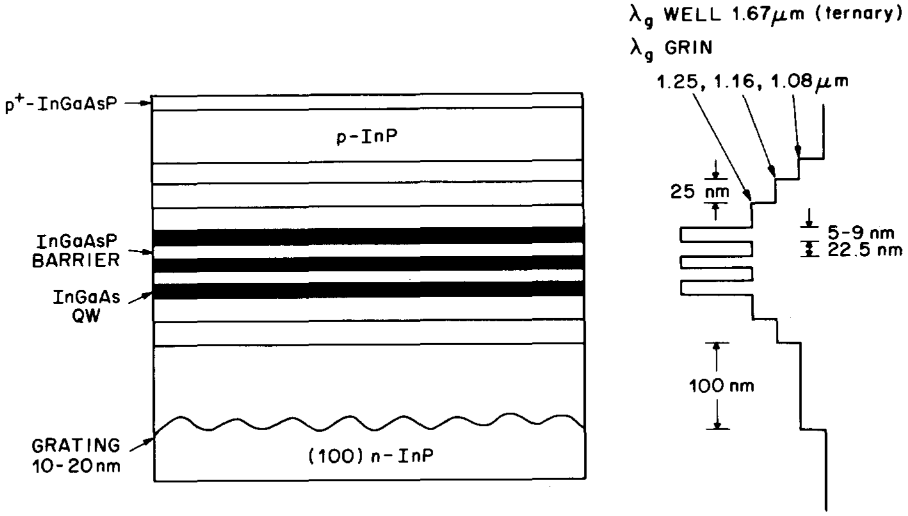

Fig. 3. Structure of the graded index multiple quantum well DFB lasers.

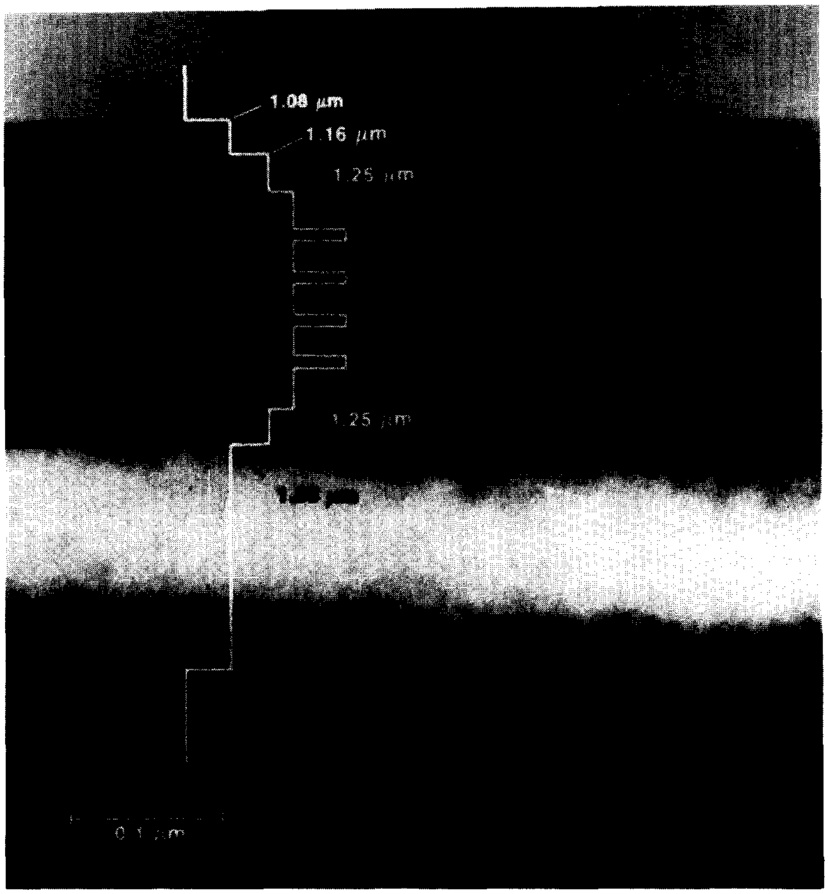

Fig. 4. TEM cross section of the graded index multiple quantum well DFB lasers. Grating as deep as 60 nm, with defect free interfaces throughout the structure was obtained reproducibly.

varies from 235 to 240nm. Fig. 1b shows the deformed gratings after heating from room temperature up to 625 °C within 3 min using infrared lamp, without any hydride gas flow into the reactor. In some cases most of the grating vanished during this short period of heating due to the mass transport of InP on the corrugated substrate. By introducing a suitable mixture of AsH_3 and PH_3 (as will be shown in fig. 2) into the reactor, the gratings could be preserved very effectively as shown in fig. 1c.

Fig. 2 shows the residual depth of the gratings, as compared to its depth before heat treatment, as a function of mole fraction of AsH_3 in the reactor. In this case the flow of PH_3 and H_2 carrier was kept constant having PH_3/H_2 ratio of 2.2×10^{-3} mole fraction. The InP gratings were heated up from room temperature to the growth temperature of 625 °C within 3 min and held at that temperature for 5 min before the sample was cooled down. A maximum residual gratings depth of around 50% is obtained but the surface of the gratings has a hazy look. By reducing the amount of AsH_3 mole fraction down to around 2×10^{-5}, clean and reasonably deep gratings can be obtained reproducibly.

4. Device fabrication

The structure of the multiple quantum well graded index separate confinement DFB lasers is shown in fig. 3. The epitaxial layers were grown on a first order gratings (100) n-InP substrate using the following growth steps: First, the grating substrate was heated up to 500 °C under a suitable mixture of AsH_3/PH_3 as described in the preceeding section. As soon as the sample temperature reached 500 °C, a 7 nm thick InGaAsP, with composition of 0.99 μm, was deposited on the gratings to further protect the gratings against thermal erosion and the temperature was then raised to the growth temperature of 625 °C under AsH_3/PH_3 mixture. A lower part of graded index confining layers with step like decreasing bandgap of 1.08 μm (100 nm thick), 1.16 and 1.25 μm (25 nm each, undoped) were then deposited with a subsequent layers of three to four InGaAs quantum wells (5 nm thick each) separated by 22.5 nm thick InGaAsP barriers of 1.25 μm composition. The upper part of the undoped graded index InGaAsP confining layers similar to the lower ones but with increasing bandgap (25 nm thick each) were then grown and a subsequent p-InP cladding layer (2 μm thick) including an undoped InP setback layer (50 nm thick) and a p-InGaAsP contact layer (Zn doped to 5×10^{18} cm^{-3}, 120 nm thick) were finally grown. The amplitude of gratings after growth vary from 10–80 nm deep depending on the amount of AsH_3/PH_3 mixture. Fig. 4 shows a transmission electron microscope (TEM) cross sectional picture of the structure. A grating depth more than 80 nm was obtained with defect free interfaces throughout the structure. The sample was further processed into buried heterostructure and regrowth was done entirely by MOVPE in only two growth steps [6].

5. Device characteristics

Fig. 5 shows the light output versus current of the GRIN-SCH-MQW-DFB lasers under CW operation at room temperature. The cavity length is

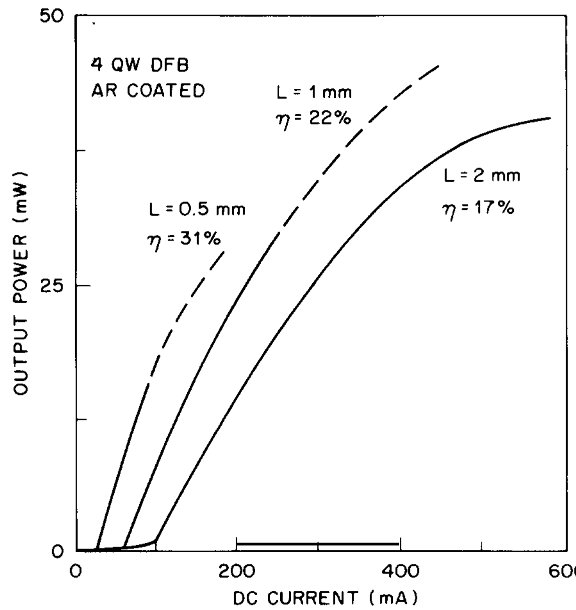

Fig. 5. Light output power versus injection current of DFB lasers with different cavity lengths.

varied from 500 μm to 2000 μm with one facet antireflection coated by single layer of SiO having a nominal thickness of around 200 nm. The reflectivity of the coated facet was estimated to be 5%. A threshold current of 22 mA was observed for devices with cavity lengths of 500 μm and increased monotonically to around 100 mA at cavity lengths of 2000 μm. Quantum efficiency as high as 31% is obtained in the shorter devices. Output power as high as 40 mW is observed. Dashed lines in the light-current curves indicate regions of non-single mode operation due to mode hopping. As expected in DFB structures, longer cavity lasers with weak gratings show a wider range of single mode operation. Fig. 6 shows the lasing spectrum of the DFB lasers with cavity length of 1 mm at the output power of 30 mW. A stable single longitudinal mode with a side mode suppression ratio better than 40 dB was observed at lasing wavelength around 1.52 μm. The coupling constant (K) of the laser is estimated to be 15–20 cm^{-1}. The linewidth dependence on the inverse output power of the DFB lasers is shown in fig. 7. The laser length was 2 mm. A minimum linewidth of 600 kHz is achieved at an output power of around 35 mW. This narrow linewidth is attributed to the low waveguide loss in the graded index quantum well structure incorporated into the DFB lasers as well as the long cavity and a low coupling coefficient in the DFB lasers [7–9]. We have also carried out a transmission experiment to determine the magnitude of dynamic chirp of the Bragg mode. The laser has been modulated from threshold at 1.7 Gb/s and the bit error rate versus power curves obtained directly and with 70 km of optical fiber. The chirp penalty is estimated to be no more than 0.25 dB, which is as much as 8–10 times less than in conventional DFB lasers.

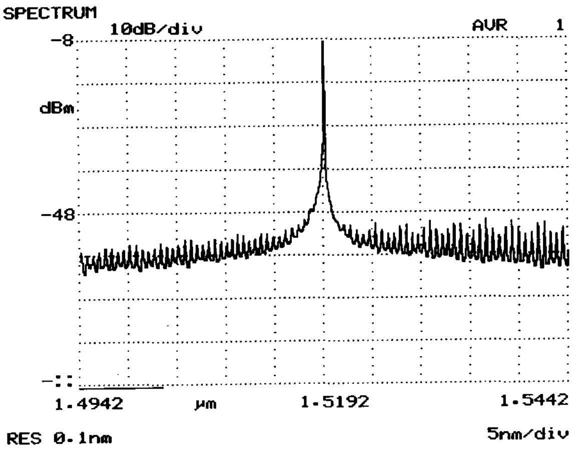

Fig. 6. Lasing spectrum of a 1 mm long DFB lasers at output power of 30 mW.

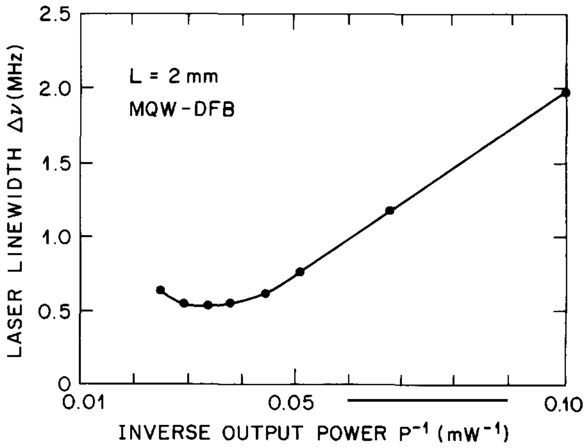

Fig. 7. Linewidth dependence on inverse output power.

6. Conclusion

We have shown a reproducible method to grow a high quality graded index quantum well DFB lasers on gratings substrate. We have also demonstrated the effectiveness of incorporating a graded index quantum well structure to improve the performance of DFB lasers. The lasers have low threshold (22 mA), high quantum efficiency (31%), very narrow linewidth (600 kHz) as well as small chirp penalty (0.25 dB) as compared to the conventional DFB lasers.

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