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Low Threshold 1.3 and 1.55 μm Strained Quantum Well Lasers

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The effect of strain on the laser threshold current density has been studied for 1.3 and 1.55 µm lasers using both InGaAsP/InP and AlGaInAs/InP materials systems. Low threshold current densities have been obtained, and 20-wavelength distributed-feedback laser arrays fabricated, using both compressive and tensile strained quantum well layers. A wide optical gain spectrum and a sub-MHz linewidth have been demonstrated.

1. INTRODUCTION

Low threshold lasers are important for minimizing the power consumption and the crosstalk of parallel optical interconnects in switching and supercomputer applications, since many lasers are needed in an array configuration. A low threshold current also helps to increase the laser CW operation temperature so that the cost of a transmitter is reduced if a thermoelectric cooler is unnecessary. Compressive strained single quantum well (QW) lasers have been theoretically proposed[1,2], and experimentally demonstrated[3-5], to have lower threshold current densities than unstrained lasers. In addition, tensile strained long wavelength lasers with low threshold current densities have been demonstrated[6]. For long wavelength lasers, most work to date has been at 1.55 µm using InGaAs wells and InGaAsP barriers. However, 1.3 µm low threshold lasers are also important because most of the fibers deployed in the field have zero dispersion at this wavelength. Some progress has been made in this area[7,8]. Although most of the work to date has been in the InGaAsP based materials system, low threshold current compressive and tensile strained InGaAs/AlGaInAs lasers have also been reported[8,9]. Lasers based on this materials system are expected to have a higher modulation speed[9]. Furthermore, lateral optical and carrier confinement may be obtained in this materials system by impurity induced disordering as in GaAs/AlGaAs lasers.

We studied the effect of strain on the laser threshold current density in the 1.3 and 1.55 µm wavelength regions using both InGaAsP/InP and AlGaInAs/InP materials systems and fabricated low threshold lasers and laser arrays for optical interconnect and subscriber loop applications.

2. OMCVD GROWTH

The laser structures were grown in a horizontal, low pressure (76 torr) organometallic chemical vapor deposition (OMCVD) reactor using arsine, phosphine, and trimethyl alkyls of gallium, indium, and aluminum. n- and p-type doping were achieved using hydrogen sulfide and diethylzinc, respectively. InP, InGaAs, and InGaAsP were grown at 625 °C, whereas AlGaInAs layers were grown at 675 °C, except for the strained AlGaInAs QWs, which were grown at 650 °C. The growth rates of InGaAs and AlGaInAs were $\sim$1.3 nm/s and that of InP was $\sim$0.69 nm/s. The growth rate of the InGaAsP alloys varied between those of InP and InGaAs. The factors governing the growth of high quality AlGaInAs are similar to those already reported for AlInAs[10].

3. QW COMPOSITION AND THICKNESS

In order to determine the In content in the compressive strained InGaAs QW, where the QW thickness is 2-3 nm, structures consisting of 10 periods of the strained QW and InP barriers were grown[11]. By growing two different structures containing QWs of the same thickness and composition but different thickness of InP, it is possible to determine the individual thicknesses and the In content of the well from the separation between the satellite peaks and the separation between the substrate peak and the zero order peak in the X-ray rocking curve. The In content obtained in this manner agreed well with that obtained from the ratio of the growth rate of InAs to that of InGaAs. Furthermore, in the case of a single tensile strained QW, where the QW thickness is 14-20 nm, the composition was determined[11] by matching the separation between the substrate and layer peaks in the experimentally obtained rocking curve with that in a simulated one obtained using dynamical diffraction theory. Again, the composition was in agreement with that estimated from the growth rates of the binary components of the ternary alloy. The composition of the AlGaInAs QWs were, therefore, estimated from the relative growth rates of InAs, AlAs, and GaAs for the mole fractions of the metal alkyls used in growing the QWs.

The QW thicknesses as estimated from growth rates and as measured by cross section transmission electron microscopy were in good agreement.

4. ADVANTAGES OF QUATERNARY QWs

In compressively strained InGaAs/InGaAsP and InGaAs/AlGaInAs 1.55μm lasers the QW thickness is only 2-3 nm, which leads to an increased sensitivity of the wavelength to thickness variations, and to a lower optical confinement factor and reduced carrier collection efficiency as compared to those in unstrained QW lasers[4,8)]. These disadvantages may be overcome by using thicker quaternary InGaAsP or AlGaInAs QWs[8,12,13)]. The introduction of a quaternary QW also allows the adjustment of the emission wavelength to either 1.3 or 1.55 μm while keeping the QW thickness and strain constant. The AlGaInAs QW is easier to implement since Al can be exchanged with Ga with no change in lattice constant, therefore making it easy to maintain the strain, in addition to the QW thickness, while tuning the emission wavelength.

In the case of tensile strained 1.55 μm lasers the InGaAs QW thickness is 14-20 nm and the emission wavelength is not sensitive to the thickness. Increasing the QW thickness by using a quaternary is not beneficial. However, the use of a 5-6 nm thick InGaAs QW in the case of 1.3 μm lasers results in the emission wavelength being slightly sensitive to the thickness. More importantly, at such QW thicknesses, the stronger quantum confinement effect on the light -hole band, as compared to that on the heavy-hole band, lowers the light-hole band either close to or even below the heavy-hole band, such that the benefits of tensile strain are not obtained. By using either InGaAsP[12)] or AlGaInAs[8)] QWs their thickness can be increased so as to not only make the emission wavelength less sensitive to the QW thickness but also maintain the light-hole band sufficiently above the heavy-hole band.

5. THERMAL STABILITY OF WAVELENGTH

The emission wavelengths of strained InGaAs/InGaAsP QW layers have been reported to blue shift with thermal treatment. This presents a problem in the fabrication of distributed feedback (DFB) lasers where the grating is defined before regrowths[14,15)]. The thermal instability has been attributed to As/P diffusion across the well-barrier interface. The problem can be overcome by using InGaAsP QWs and barriers with the same As and P content in both layers[16)] or by using InGaAs/AlGaInAs QWs. Substrates with higher dislocation densities, such as those doped with Sn, have also been shown to increase the thermal stability of InGaAs/InGaAsP QWs[15)].

6. THRESHOLD CURRENT DENSITY OF STRAINED LAYER SINGLE QW LASERS

Oxide stripe lasers with 50 μm contact opening were made to evaluate the threshold current density of the strained layer single QW active layers. For 1.55 μm lasers, $In_xGa_{1-x}As$ (10-12.5 nm thick)was chosen for the tensile strained or unstrained QW. For the compressive strained well, a quaternary, $Al_{0.09}Ga_{0.22}In_{0.69}As$ (8.5 nm thick) was chosen. The ternary QW is in the middle of a step graded-index separate confinement heterostructure (GRINSCH)[6)] made of InGaAsP quaternary layers. The quaternary QW is in the middle of a continuous GRINSCH made of AlGaInAs quaternary layers[8)]. The undoped quaternary layer next to the QW has a bandgap wavelength of 1.2 μm.

The strain dependence of threshold current density was obtained using 2 mm long devices. A long cavity was used to reduce the mirror loss per unit length such that the laser operates in the transparency-limited region where the strain is most effective. For the lattice matched single QW lasers the threshold current density is 769 A/cm^2. The threshold current density decreases monotonically with either increasing compressive or increasing tensile strain. Both types of strain are effective in reducing threshold current , although the mechanisms are different[17)]. The threshold current densities were 220 A/cm^2 and 190 A/cm^2 for lasers with $In_{0.3}Ga_{0.7}As$ (-1.6% strain) and $Al_{0.09}Ga_{0.22}In_{0.69}As$ (+1.3% strain) QWs, respectively. For 4 mm long tensile strained (-1.6%) lasers the threshold current density reduced to 197 A/cm^2.

For 1.3 μm lasers, a single $Al_{0.18}Ga_{0.12}In_{0.7}As$ well (8.8 nm thick) was used for the compressive strained QW and a single $Al_{0.07}Ga_{0.54}In_{0.39}As$ well (14.4 nm thick) for the tensile strained QW. The GRINSCH consists of a 0.1 μm thick continuously graded AlGaInAs layer with a bandgap wavelength graded from 0.96 to 1.1 μm on either side of the QW[8)]. For compressive strained lasers, a minimum threshold current density of 100 A/cm^2 was measured on 5 mm long devices. This is the lowest value reported for compressive strained QW lasers in the 1.3 and 1.55 μm wavelength regions. The minimum threshold current density of tensile strained lasers was 188 A/cm^2 for 5 mm long devices. The lasing light was verified to be TE-polarized for compressive and TM-polarized for tensile strained lasers.

7. LOW THRESHOLD NARROW STRIPE STRAINED QW LASERS

1.5 μm tensile strained single QW lasers were fabricated with a semi-insulating planar buried heterostructure (SIPBH) to confine the carriers and the optical mode[6)] The active region was 1.5 μm wide and consisted of a 20 nm thick $In_{0.41}Ga_{0.59}As$ well in the middle of a GRINSCH as mentioned above. With high reflection facet coatings, a threshold current as low as

2 mA was obtained at 15 °C from 250 μm long lasers. Because of the low internal loss ($\sim$ 5 cm^{-1}), a front facet quantum efficiency of 30 % was achieved in spite of the high reflection coating on the front facet. The threshold current remains less than 10 mA up to 90 °C[6]. A maximum CW operating temperature of 135 °C was obtained from 1 mm long lasers.

Ridge waveguide lasers were also fabricated using the 1.3 μm compressive strained single QW material. The waveguide was 3.5 μm wide. The threshold current of 300 μm long lasers was 2 mA when both facets were high-reflection coated[18]. The CW threshold current at 100 °C heat sink temperature was 14 mA[18], which is desirable for subscriber loop applications.

8. STRAINED LAYER QW DFB LASER ARRAYS

DFB laser arrays are compact attractive light sources for use in wavelength division multiplexing (WDM) lightwave communication systems to increase the information transmission capacity, and in multi-wavelength switching networks to route information by wavelength. The wide optical gain spectrum (150 - 200 nm) of strained QW active layers and the small linewidth enhancement factor (α = 1.5)[19] of the tensile strained QW active layer can be exploited in DFB laser arrays. 20-wavelength DFB laser arrays were fabricated using λ / 4-shifted first order gratings. The grating period was varied to change the wavelength. The active layers were either 3 compressive strained $In_{0.8}Ga_{0.2}As$ (2 nm thick) with λ_g = 1.3 μm InGaAsP barriers or a single tensile strained $In_{0.4}Ga_{0.6}As$ (20 nm thick) QW with λ_g = 1.2 μm InGaAsP barriers. A SIPBH structure was grown for lateral optical and carrier confinement. Afterwards, channels were etched along both sides of the active stripes to isolate each laser from its neighbor and to further reduce parasitic capacitances. The cavity, formed by cleaving, was 250 and 875 μm long for compressive and tensile strained DFB laser arrays, respectively. Antireflection facet coatings were applied to insure single mode operation.

For compressive strained arrays, the lasing wavelengths ranged from 1459.2 to 1590.76 nm, corresponding to a channel spacing of 7 nm. The side-mode suppression ratio was better than 30 dB. The wavelength detuning is in the range of +26 to -79 nm. The maximum intrinsic 3 dB bandwidth was measured to be 16 GHz, with negative wavelength detuning, using a parasitic free optical modulation technique.

For tensile strained single QW DFB laser arrays the lasing wavelength ranges from 1485 to 1541 nm, corresponding to a channel spacing of 3 nm. The wavelength detuning is in the range of -18 to + 32 nm. A minimum linewidth of 180 kHz (corresponding to a linewidth-power product of 1.5 MHz-mW) was measured by the delayed self heterodyne method.

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