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Strained-Layer InGaAs Multiple Quantum Well Lasers Emitting at 1.5 Micron Wavelength

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Strained-layer InGaAs/InP MQW lasers emitting at 1.5 μm wavelength have been fabricated. For the 1.8% biaxially compressed $In_{0.8}Ga_{0.2}As$ MQW devices, the predicted enhanced performance over 1.5 μm wavelength lattice matched InGaAs MQW devices has been observed. These SL-MQW devices show differential external efficiencies as high as 82%, characteristic temperatures (T_0) as high as 97K and CW output powers as high as 200 mW. Lifetests over 8500 hrs demonstrate the excellent reliability of these devices.
For the first time, 0.9% biaxially tensioned SL-$In_{0.4}Ga_{0.6}As$ MQW devices are reported, showing TM polarised 1.5 μm wavelength emission as a result of the tensile strain-induced reversal of the heavy hole-light hole energy levels.

1. Introduction

$In_{0.53}Ga_{0.47}As$ multiple quantum well (MQW) lasers at 1.5 μm wavelength have yielded several advantages over bulk InGaAsP lasers at this wavelength such as reduced spectral linewidth[1], enhanced relaxation oscillation frequency[2] and enhanced output power[3,4]. However, key parameters such as threshold current, the temperature dependence of the threshold current (T_0) and the differential external efficiency (η) have not improved as significantly as reported for (M)QW lasers in the GaAs/AlGaAs system.

Recently, several reports[5,6] predicted that the combination of strain and quantum-confinement gives rise to novel electronic properties as a result of the strain-induced modification of the band structure. This could be used either to improve the performance of strained-layer (SL) $In_xGa_{1-x}As$ MQW lasers over existing 1.5 μm wavelength MQW lasers or to exploit new properties that cannot be obtained for lattice matched MQW structures. Since these structures require the growth of very thin layers with abrupt interfaces[7,8], which are embedded in phosphorus-containing layers, (low-pressure) Organometallic Vapour Phase Epitaxy (LP-OMVPE) is one of the best suited growth techniques. So far, only a few studies on 1.5 μm wavelength SL-$In_xGa_{1-x}As$ MQW lasers have been reported[8-12].

This paper will discuss the potential advantages of 1.5 μm wavelength SL-InGaAs MQW lasers. Device characteristics of SL-InGaAs MQW lasers with the wells grown under biaxial compression and biaxial tension will be reported.

2. Potential advantages of SL-InGaAs MQW lasers

High quality heterostructures can be grown from lattice-mismatched materials as long as the lattice mismatch can be accommodated by elastic tetragonal deformation of the unit cell. The loss of the cubic symmetry can result in a significant distortion of the band structure, particularly in regions of degeneracy such as the top of the valence band. The deformation of the $In_xGa_{1-x}As$ unit cells, with indium fractions $x>0.53$, $x=0.53$ and $x<0.53$, grown coherently on (001) InP and the strain-induced band structure modification are shown in fig.1. For $In_xGa_{1-x}As$ grown under biaxial compression, i.e. with $x>0.53$, the strain-induced modification of the band structure can be summarized as follows: the bandgap is increased, the LH-HH degeneracy near the zone centre is lifted and this energy splitting of the valence subbands is enhanced by the application of QWs, the HH effective mass in the in-plane direction (k_x, k_y) is reduced near the zone centre and the conduction band discontinuity is increased. The reduced in-plane HH-mass lowers the carrier density needed for popudensity needed for population inversion, i.e. a reduction of the threshold current is expected. This, together with the increased conduction band discontinuity, which reduces the hetero-barrier carrier leakage, and the increased bandgap and increased energy separation of the valence subbands is expected to result in reduction of the amount of Auger Recombination and Intervalence band absorption, respectively.

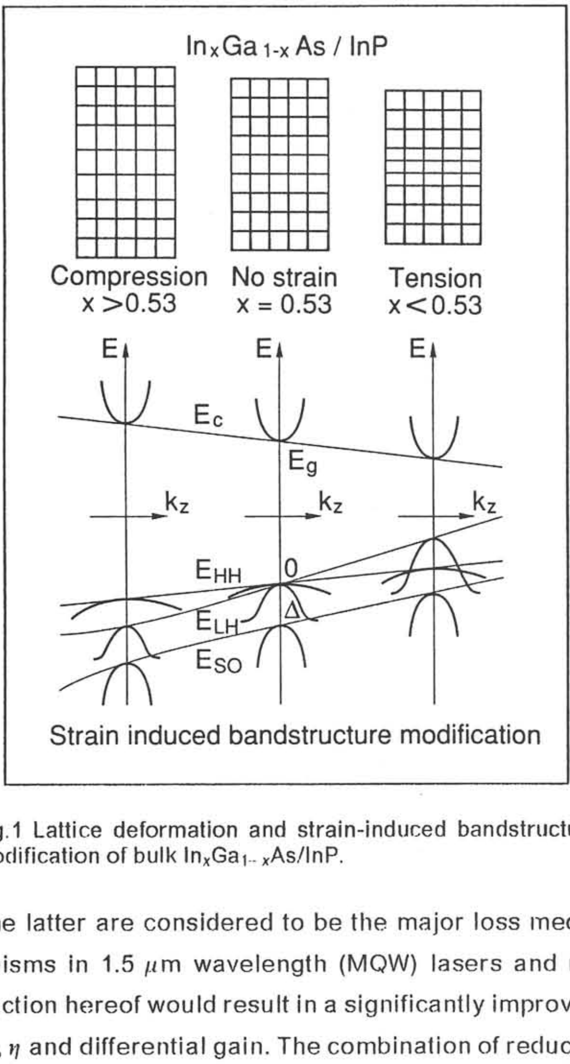

Fig.1 Lattice deformation and strain-induced bandstructure modification of bulk $In_xGa_{1-x}As$/InP.

The latter are considered to be the major loss mechanisms in 1.5 μm wavelength (MQW) lasers and reduction hereof would result in a significantly improved T_0, η and differential gain. The combination of reduced threshold current, enhanced T_0 and η give excellent prospects for high power operation.

For SL-$In_xGa_{1-x}As$ MQW structures grown under sufficient biaxial tension, i.e. with $x<0.53$, the energy levels of HH and LH are reversed as shown in fig. 1 and hence TM polarised emission is expected because the TM mode couples exclusively to the LH states. This cannot be obtained in lattice matched or biaxially compressed MQW structures.

3. SL-In_xGa_{1-x}As MQW lasers

3.1. Fabrication and device structure

Double heterostructures containing SL-In_xGa_{1-x}As/InGaAsP MQW active layers were grown by LP-OMVPE using trimethyl alkyls of gallium and indium, pure arsine and phosphine[8,10] . Hydrogen sulfide (diluted to 0.1% in hydrogen) and diethyl zinc were used as n-type and p-type dopants, respectively. Double channel planar buried heterostructure (DCPBH) lasers were fabricated by standard technology, which includes etching of the channels and subsequent LPE regrowth of current blocking and contact layers. Devices, mounted p-side down on Cu heat sinks, with cavity lengths ranging from 200 to 1500 μm, with as-cleaved and coated mirrors, were evaluated.

3.2. Biaxially compressed $In_{0.8}Ga_{0.2}$As MQW lasers

The SL-active layers of the DCPBH devices consist of two, four, six and eight $\simeq$ 30 Å-thick $In_{0.8}Ga_{0.2}$As wells which are 1.8% biaxially compressed. The lattice matched InGaAsP ($\lambda = 1.3$ μm) barrier and separate confinement layers were zinc doped to a level of $N_A - N_D = 5.10^{17}$ cm^{-3}.

Uncoated 2-well devices with 1000 μm cavity length lased under pulsed conditions at 1.55 μm wavelength corresponding to the QW levels. After HR coating of the mirrors (R_f=80%, R_r= 90%) the CW threshold current at 20 °C was as low as 29 mA. CW lasing at $\lambda = 1.55$ μm was maintained up to 40 °C.

SL-$In_{0.8}Ga_{0.2}$As MQW lasers with 4, 6 and 8 wells all lased at 1.55 μm wavelength. The 4-well devices showed threshold currents of 25 to 35 mA for cavity lengths of 265 μm to 1020 μm, respectively. The threshold current could be reduced to 10 mA for 200 μm cavity length devices by reducing the mirror losses (R_f=60%, R_r =90%). For 6-well devices the threshold current was only 20 mA for 250 μm long devices and increased to 40 mA for 1000 μm long devices. The threshold current of 8-well devices was significantly higher than for the 4-well and 6-well devices; 42mA and 80 mA for 250 and 750 μm cavity length devices, respectively. This was already indicated by the reduced 1.55 μm PL intensity which may result from defects due to the large total thickness of the SL-$In_{0.8}Ga_{0.2}As$ wells.

The SL-MQW devices exhibit very large differential external efficiencies. Fig. 2 shows the η (right) and inverse η (left) versus the cavity length of 4-well devices. The 265 μm cavity length devices showed η's as high as 82%. This is higher by almost a factor of two compared to 1.5 μm wavelength lattice matched InGaAs MQW lasers[13,14]. From the slope and the interception with the vertical axis, the cavity loss (α) and the internal efficiency (η_i) were deduced to be 13 cm^{-1} and close to 100%, respectively. The η_i of the 6-well and 8-well devices were 90% and 67%, respectively and 250 μm cavity length 8-well devices showed an η as high as 52%. The enhanced η, η_i and the low α observed for these 1.55 μm wavelength SL-devices are an indication of a significant reduction in the amount of Intervalence band absorption.

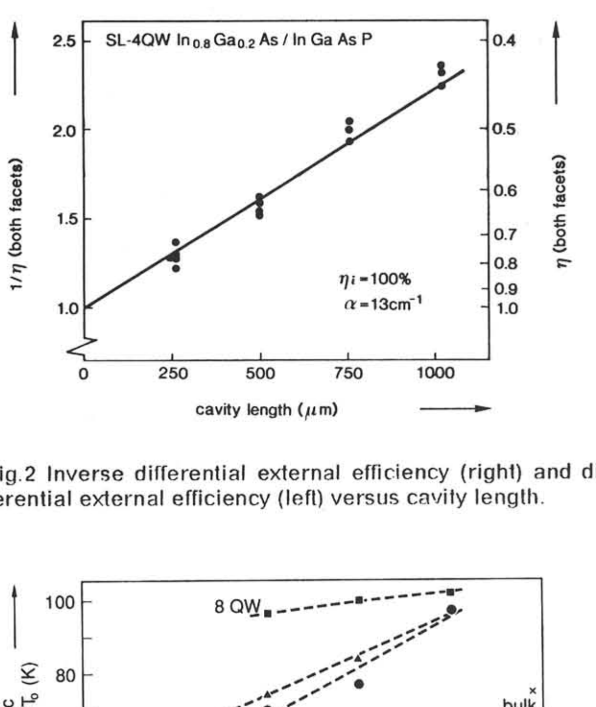

Fig.2 Inverse differential external efficiency (right) and differential external efficiency (left) versus cavity length.

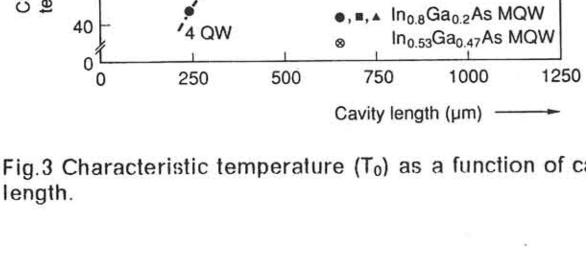

Fig.3 Characteristic temperature (T_0) as a function of cavity length.

The T_0 values between 20 and 50 °C for the SL-MQW DCPBH devices are plotted versus the cavity length in fig. 3. As a reference, the T_0 values of 1.5 μm wavelength lattice matched MQW and bulk InGaAsP lasers are shown also. For the SL-devices the T_0 value increases with cavity length as shown in fig. 3. A T_0 as high as 97 K was measured for 1000 μm cavity length SL-MQW devices, whereas lattice matched InGaAs MQW devices showed T_0 values at room temperature ranging from 50-68K[9,14] The bulk InGaAsP DCPBH device showed a T_0 of 76K. The T_0 value of the 8-well devices may be overestimated as a result of the high threshold current for these devices. The significantly improved T_0 of the SL-MQW devices compared to the lattice matched MQW and bulk devices may be attributed to the reduced Auger Recombination.

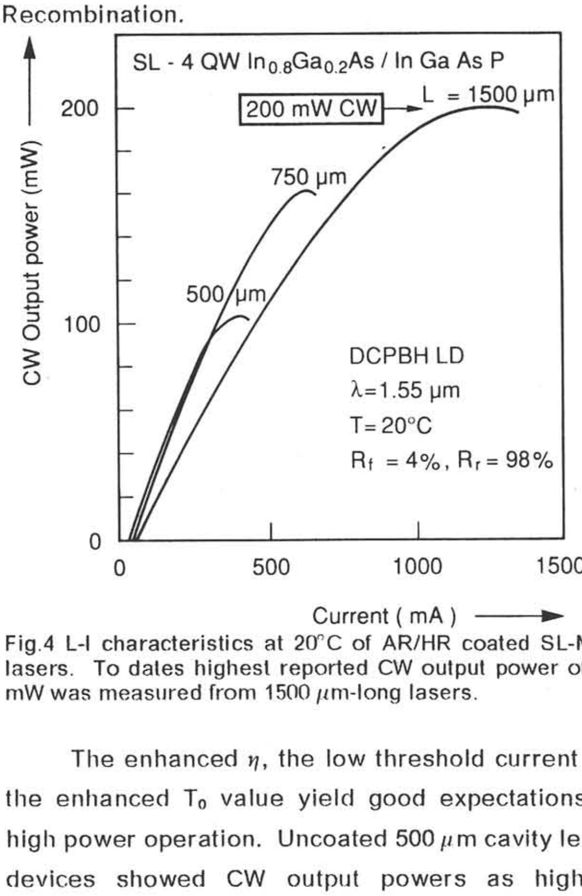

Fig.4 L-I characteristics at 20°C of AR/HR coated SL-MQW lasers. To dates highest reported CW output power of 200 mW was measured from 1500 μm-long lasers.

The enhanced η, the low threshold current and the enhanced T_0 value yield good expectations for high power operation. Uncoated 500 μm cavity length devices showed CW output powers as high as 75 mW/facet[10]. Fig. 4 shows the L-I characteristics at 20 °C of 500, 750 and 1500μm cavity length AR/HR coated DCPBH devices. CW output powers as high as 100 mW and 160 mW were measured from 500 μm and 750 μm cavity length devices. An output power as high as 200 mW was measured from 1500 μm long

SL-MQW devices which is to the best of the author's knowledge the highest output power reported to date at 1.55 μm wavelength. The high performance of this large cavity length, 1.8% biaxially compressed devices indicates the excellent homogeneity of the SL-MQW structures.

Uncoated SL-$In_{0.8}Ga_{0.2}As$ MQW DCPBH lasers, which were not screened, were subjected to a lifetest at 60 °C. Four-well devices were tested for 5400 hrs at 5 mW/facet and subsequently for 3000 hrs at 20 mW/facet output power. The increase in threshold current was typically below 5% for the total test time. No variation of the lasing wavelength was observed. This demonstrates for the first time the excellent reliability of 1.5 μm wavelength SL-$In_{0.8}Ga_{0.2}As$ MQW DCPBH lasers with the wells under 1.8% biaxial compression.

3.3. Biaxially tensioned $In_{0.4}Ga_{0.6}As$ MQW lasers

The SL-active region consisted of four $\simeq$ 80 Å-thick $In_{0.4}Ga_{0.6}As$ wells which are under 0.9% biaxial tension.

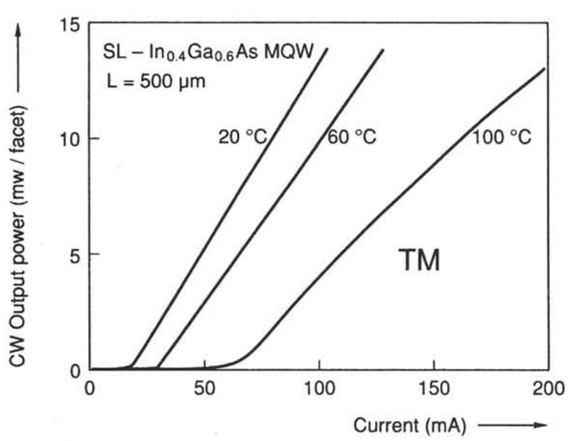

Fig. 5 L-I characteristics of as-cleaved $In_{0.4}Ga_{0.6}As$ (0.9% biaxial tension) MQW lasers.

Fig. 5 shows the CW L-I characteristics of a 500 μm cavity length laser up to 100 °C heat sink temperature. The threshold current was 17, 30 and 63 mA at 20, 60 and 100 °C, respectively. At 100 °C the CW output power exceeded 15 mW/facet and at 20 °C the output power was as high as 50 mW/facet. All devices lased in the lowest order TM mode which demonstrates the reversal of the HH and LH energy states which may also explain the low threshold current.

4. Summary

Strained-layer (SL) $In_xGa_{1-x}As$ MQW lasers emitting at 1.5 μm wavelength with biaxially compressed and biaxially tensioned wells were fabricated by the hybrid LP-OMVPE/LPE technique. The lasers with 1.8% biaxially compressed $In_{0.8}Ga_{0.2}As$ wells showed CW output powers as high as 200 mW, differential external efficiencies as high as 82% and T_0 values as high as 97K. This significant improved performance over lattice matched InGaAs MQW devices is interpreted to result from the strain-induced modification of the band structure resulting in a reduced amount of Auger recombination and Intervalence band absorption. Lifetesting for 8500 hrs shows the excellent reliability of these devices.

For the first time the consequences of the strain-induced reversal of the heavy hole-light hole states in 0.9% biaxially tensioned $In_{0.4}Ga_{0.6}As$ MQW lasers are demonstrated. These devices emitted in the lowest order TM mode, which cannot be obtained in lattice matched and biaxially compressed MQW devices.

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