A New InGaAs/InGaAsP δ-Strained Multiple-Quantum-Well Laser Grown by Chemical-Beam Epitaxy

L. Yang, M. C. Wu, Y. K. Chen, W. T. Tsang, S. N. G. Chu, and A. M. Sergent

Abstract—**We proposed and demonstrated a δ-strained multiple-quantum-well laser in which the quantum well is composed of a thin strained layer (~ 12-Å $In_xGa_{1-x}As$) sandwiched by lattice-matched ($In_{0.53}Ga_{0.47}As$) layers. A threshold current density of 510 A/cm^2 was obtained from the broad-area lasers having four δ-strained quantum wells and a cavity length of 3 mm, with an emission wavelength near 1.55 μm. The use of a δ-strained quantum well provides an additional degree of freedom in optimizing the amount of strain and thickness of the active layer in improving the device performance.**

RECENTLY low threshold current and high output power from multiple-quantum-well (MQW) lasers grown on InP substrates have been demonstrated by both metalorganic vapor-phase epitaxy (MOVPE) [1]-[4] and chemical-beam epitaxy (CBE) [5]-[6]. By using a strained-layer MQW, the degeneracy of the valence band is lifted. For the case of compressive strain, the reduction of the hole effective mass may provide a larger gain, and also reduces the Auger recombination process [7]-[9] much more than those of the unstrained case. Therefore, the threshold current density was further reduced [6], [11]. Experimentally, the compromise between the amount of the strain and the associated critical layer thickness has set the optimal atomic ratio of indium in the $In_xGa_{1-x}As$ active layer near 0.65 for the case of compressive strain [6]. For larger strain, the quantum-well width needs to be thinner to avoid the formation of a mismatch defect. However, the carrier capture time of a quantum well also increases substantially when the quantum-well size is decreased to the ~30 Å range. As a result, the carrier injection efficiency into the quantum wells decreases with narrowing quantum well width, thus increasing the threshold current density. In this letter, we propose and demonstrate the use of δ-strained layers sandwiched by lattice-matched layers for the quantum wells. Using lattice-matched layers, the width of the quantum wells is not limited by the amount of strain. As a result, it is possible to optimize the strain of the active layer and the quantum-well thickness separately for laser structure design. Our experimental result has shown the promise of such a structure by a threshold current density as low as 510 A/cm^2 with an emission wavelength of ~1.55 μm. Further improvement on either threshold current density or output power is expected when the number of quantum wells, layer thickness, and alloy composition is optimized.

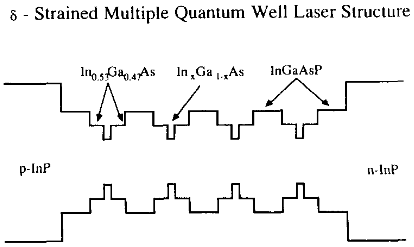

Fig. 1. Layer structure of the δ-strained multiple-quantum-well laser, employing a separate confinement heterostructure.

The idea of a δ-strained quantum well (δ-S QW) is illustrated in Fig. 1. The quantum well is composed of a strained layer sandwiched by lattice-matched layers. The carriers injected from the barrier layers are collected more efficiently due to a wider quantum-well width compared to that without the lattice-matched layers. The δ-S QW structure can be used to optimize the confinement of the carriers and the thickness of the strained layer which modifies the valence band structure. In principle, if needed, any combination of strained layers suitable for device optimization can be employed. For example, strain-compensation layers (with opposite strain) can be inserted near both sides of the quantum well or even in the barrier layer.

The layer structure shown in Fig. 1 was grown by chemical-beam epitaxy (CBE) on a (100) n$^+$-InP substrate. Sn and Be thermal beams were employed for n and p dopings, respectively. The detailed growth condition was described elsewhere [12]. The growth started with a 0.6-μm Sn-doped (2 × 10^{17}/cm^2) InP buffer layer. The active layer consisted of four 46-Å $In_{0.53}Ga_{0.47}As$/12-Å $In_xGa_{1-x}As$/36-Å $In_{0.53}Ga_{0.47}As$ δ-SQW's separated by three 210-Å-thick InGaAsP (lattice-matched, $\lambda_g = 1.25$ μm) barriers. For comparison, three samples were grown with x values of 0.53, 0.8, and 1.0. For the case of $x = 0.53$, it is the lattice-matched quantum well. For the case of $x = 1.0$, the strained

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Fig. 2. TEM photograph of the active layers for the case of $x = 0.8$ in the δ-S MQW laser.

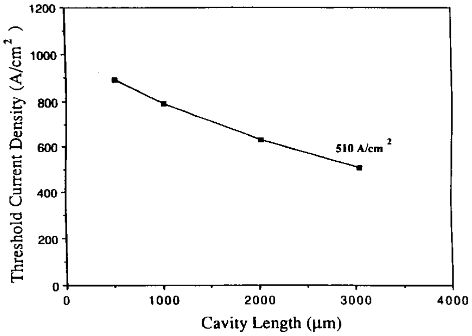

Fig. 3. Threshold current density of the δ-S MQW laser as a function of the cavity length for the case of $x = 0.8$.

layer is simply an InAs binary compound. The SCH InGaAsP waveguide layers on both sides of the active layer were of uniform composition ($\lambda_g = 1.25$ μm) and were each 500 Å thick. The top Be-doped InP ($2 \times 10^{17}/\text{cm}^3$) cladding layer was 1.3 μm thick. Finally, a p$^+$-InGaAsP top layer served as the ohmic contact layer and the etching mask for mesa etching. To achieve abrupt interfaces, the growth was interrupted by switching the metalorganic group III flow into the vent, while leaving the substrate stabilized by the hydride gas(es). To evaluate the threshold current density while excluding the dependence of the laser fabrication process, broad-area lasers (defined by a 55-μm-wide SiO$_2$ window) with various lengths were fabricated.

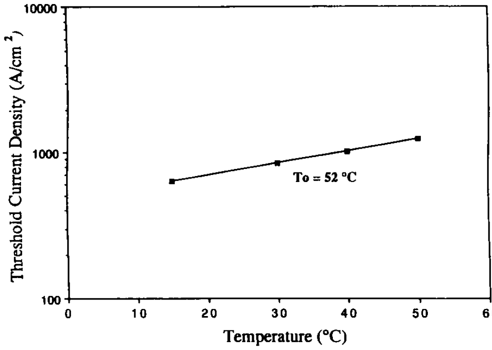

Fig. 4. Threshold current density of the δ-S MQW laser as a function of temperature. A T_0 of 52 K was found for the case of $x = 0.8$.

Fig. 2 shows a transmission electron microscope (TEM) photograph of the active layer for the case of $x = 0.8$. The image of the δ-strained layers is seen clearly. The thickness of each layer agrees with the nominal value estimated from the growth rate found from the thick layer calibration run. We found that the first two wells exhibited high-quality interfaces, as was usually obtained in the unstrained quantum-well case. However, in the third and fourth wells, the interfaces from InGaAs to InGaAsP are not as uniform. We suspect that it is due to the strain of the wells. This suggests that even better device performance can be obtained by optimizing the number of δ-strained wells and their thicknesses.

We conducted a series of experiments without changing the growth conditions, except for the x values of the δ-strained layers. Fig. 3 depicts the threshold current density as a function of cavity length for the case of an $x = 0.8$ strained layer. The threshold current density and external quantum efficiency were 890 A/cm^2 and 20% for a 500-μm-long cavity, respectively. The J_{th} decreases to 510 A/cm^2 for a 3-mm-long cavity. The emission wavelength is 1.55 μm. The performance of the δ-SMQW laser with $x = 0.8$ is superior to those with $x = 0.53$ or 1.0. The threshold current density (500-μm-long cavity) for $x = 0.53$ (lattice-matched case) was found to be 1.1 kA/cm^2 in this series of experiments, with an emission wavelength of 1.51 μm. For the case of $x = 1$ (InAs strained layer), the threshold current density (from a 500-μm-long cavity) was found to be 2.7 kA/cm^2, with an emission wavelength of 1.52 μm. This wavelength is shorter than the case of $x = 0.8$, which may be due to lasing at the second electron subband. Nevertheless, it is quite remarkable that the laser still lases with this much strain.

The threshold current density as a function of temperature is shown in Fig. 4. A characteristic temperature T_0 of 52 K is extracted, which is found to be slightly higher than that (45°C) of the lattice-match MQW laser [5]. The performance of the δ-S MQW laser should be further improved by optimizing the number of quantum wells, the thicknesses and compositions of the active layers, and by employing the graded-index SCH (GRINSCH) structure.

In summary, we have demonstrated the first InGaAs/InGaAsP δ-S MQW laser. The broad-area threshold current densities of SCH lasers were found to be as low as 890 and 510 A/cm^2 for the cavity lengths of 500 μm and 3 mm, respectively.

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