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STRAINED-LAYER 1·5 μm WAVELENGTH InGaAs/InP MULTIPLE QUANTUM WELL LASERS GROWN BY CHEMICAL BEAM EPITAXY

Indexing terms: Lasers, Semiconductor lasers

A substantial reduction is reported in the threshold current densities for 1·5 μm wavelength $In_xGa_{1-x}As/In_xGa_{1-x}As_{1-y}P_y$ strained-layer multiple quantum well (SL-MQW) lasers over lattice-matched MQW lasers. Threshold current density was found to depend sensitively on the InAs content x and thickness d of the $In_xGa_{1-x}As$ quantum wells. Threshold current densities as low as 370 A/cm² and internal quantum efficiency of 90% were obtained for separate confinement heterostructure SL-MQW lasers having four quantum wells and with $x = 0{\cdot}65$ and $d = 5$ nm. Such a threshold current density is among the lowest values obtained thus far for 1·5 μm wavelength InGaAs/InGaAsP MQW lasers. The present lasers were grown by chemical beam epitaxy.

Recently, 1·5 μm wavelength $In_xGa_{1-x}As/In_xGa_{1-x}As_{1-y}P_y$ multiple quantum well (MQW) lasers were shown to have high output power,[1] narrow linewidth[2] and reduced threshold current density J_{th}.[3–6] In this paper, we report a further reduction of the J_{th} for strained-layer MQW (SL-MQW) lasers grown by chemical beam epitaxy (CBE). A study is also made of the effect of InAs content x and quantum well thickness d on the J_{th} of SL-MQW lasers.

Standard separate confinement heterostructure (SCH) devices were grown by CBE using previously described procedures.[7–9] To have a meaningful comparison of J_{th} of unstrained and strained-layer MQW lasers, all the lasers studied in this experiment have four quantum wells. The InAs content x and quantum well thickness d were varied while keeping the barrier InGaAsP (1·25 μm composition) thickness constant at 17 nm. The SCH InGaAsP waveguide layers on both sides of the active MQWs were of uniform composition (1·25 μm composition) and 40 nm thick. Sn and Be thermal beams were employed for n and p dopings, respectively. For broad-area J_{th} evaluation, 55 μm wide oxide-stripe lasers were fabricated with cavity lengths of 0·5–3·5 mm.

Threshold current densities against InAs content x in the $In_xGa_{1-x}As$ quantum wells are shown in Fig. 1*a* for lasers with quantum well thickness $3\,nm \le d \le 4\,nm$ and laser cavity lengths of 500 μm. A minimum J_{th} was obtained for $x \approx 0{\cdot}6$–$0{\cdot}65$ (compressive strain). J_{th} increased rapidly for $x \gtrsim 0{\cdot}7$ (compressive strain) and $x \lesssim 0{\cdot}5$ (tensile strain). Note that the curve is not symmetric with respect to the lattice-matched composition. In Fig. 1*b*, the J_{th} against quantum well thickness d for a different amount of strain is shown. The close clustering of the data for each x and d indicates the excellent reproducibility of CBE growth. The present results show that for MQW lasers, the J_{th} depends sensitively on the type and amount of strain and the well thickness. Careful optimisation of layer structure is needed. Although these results demonstrate the behaviour of J_{th} for four quantum wells, similar trends can be expected for lasers with other numbers of wells.

To demonstrate more clearly the reduction in J_{th} for optimally strained-layer MQW lasers over unstrained-layer MQW lasers, we compare their J_{th}s as a function of cavity length as shown in Fig. 2. The SL-MQW lasers have an $x = 0{\cdot}65$ and $d = 5$ nm. Similar MQW lasers[9] also grown by CBE but unstrained have $J_{th} = 860$ A/cm² for a 500 μm long cavity and ~590 A/cm² for 1500–3500 μm long cavities. These values are similar to those for unstrained MQW lasers grown by metalorganic vapour phase epitaxy (MO-VPE) but incorporating the more advanced graded-index SCH (GRIN-SCH). Substantial reduction in J_{th} was obtained for the SL-MQW lasers. A J_{th} as low as 580 A/cm² was obtained for a cavity length of 500 μm and 370 A/cm² for cavity lengths ≳ 1500 μm.

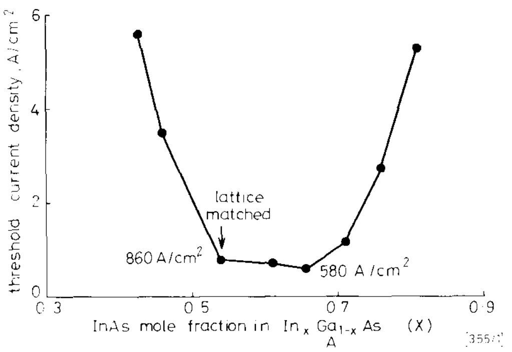

Fig. 1A *Threshold current densities against InAs mole fraction x in $In_xGa_{1-x}As$ quantum wells*

4 SL-MQW
30 Å ≤ d ≤ 40 Å
Cavity length = 500 μm

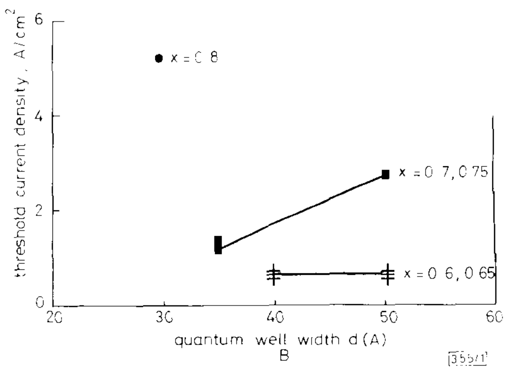

Fig. 1B *Threshold current densities against quantum well thickness d for different amounts of strain*

4 SL-MQW
Cavity length = 500 μm

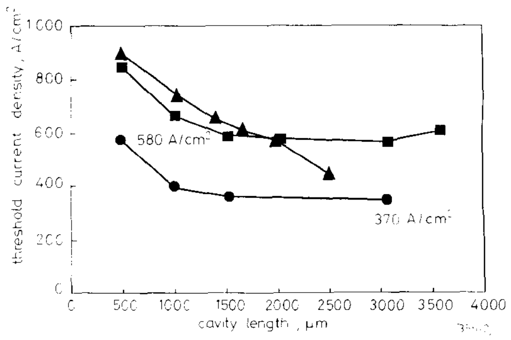

Fig. 2 *J_{th} of strained-layer MQW lasers compared with lattice-matched CBE-grown and MO-VPE-grown MQW lasers*

4 SL-MQW
$x = 0{\cdot}65$
$d = 50$ Å
▲ MOVPE GRIN-SCH MQW
■ CBE SCH MQW
● CBE strained SCH MQW

Such J_{th}s are among the lowest ever obtained for $1{\cdot}5\,\mu m$ wavelength SL-MQW lasers having four quantum wells. An internal quantum efficiency η_i of 91% was measured from a plot of inverse external quantum efficiency against cavity length. This is somewhat higher than that obtained for unstrained MQW lasers ($\sim 80\%$).

An interesting question is whether or not Auger recombination is reduced in SL-MQW lasers. The change in separation between heavy and light hole bands through the introduction of strain in the quantum wells is expected to affect the conduction band–heavy hole band–heavy hole band–light hole band (CHHL) Auger process. However, Temkin *et al.*[10] observed no improvement in the threshold-temperature dependence T_0 of MO-VPE grown SL-MQW lasers over lattice-matched MQW lasers. They are characterised by T_0s in the range of 45–50. Furthermore, they observed no difference between pulsed broad-area lasers and CW buried heterostructure lasers implying negligible contribution of leakage current around the regrown interface and thermal resistance to the temperature dependence of the threshold. To ensure the latter two effects are not present, we choose to measure the T_0 of the SL-MQW using broad-area lasers bonded *p*-side down on copper heatsinks and under low duty-cycle pulsed operation. Fig. 3 shows the J_{th} as a function

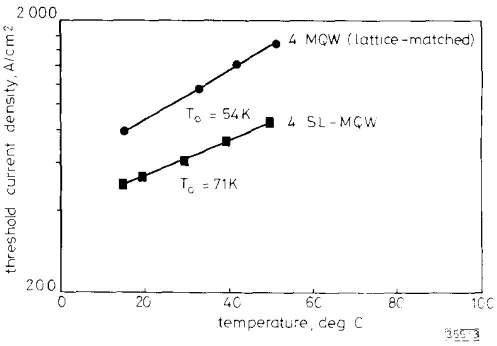

Fig. 3 *J_{th} as function of heat-sink temperature for lattice-matched and SL-MQW lasers*

Cavity length = $1000\,\mu m$

of heatsink temperature for the SL-MQW laser having $x = 0{\cdot}65$, $d = 5$ nm and cavity length = $1000\,\mu m$. A T_0 of 71 K was measured in the temperature range of 10–50°C. The measured T_0 for lattice-matched MQW lasers also grown by CBE is ~ 54 K. Considering the fact that the T_0 for these SL-MQW lasers is still relatively low, we may have to consider this improvement to be still inconclusive. Nevertheless, it is not likely that any significant improvement in T_0 can be expected by introducing strain into the quantum wells. Future improvements in the high temperature performance of long wavelength lasers will have to come from a further reduction in the threshold current, optimisation of facet reflectivity and cavity length, and reduction in power dissipation and thermal resistance.

In summary, we report a substantial reduction in J_{th} for SL-MQW lasers over lattice-matched MQW lasers grown by CBE. J_{th} was found to depend sensitively on the InAs content x and thickness of the $In_xGa_{1-x}As$ quantum wells. J_{th} as low as $370\,A/cm^2$, $\eta_i = 91\%$ and $T_0 = 71$ K were obtained for SCH-SL-MQW lasers having $x = 0{\cdot}65$ and $d = 5$ nm. Such a J_{th} represents the lowest value obtained thus far for $1{\cdot}5\,\mu m$ wavelength InGaAs/InGaAsP MQW lasers. The present results also demonstrated that CBE is capable of producing high quality quantum well lasers.

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NOISE REDUCTION BASED ON MICROPHONE ARRAY WITH LMS ADAPTIVE POST-FILTERING

Indexing terms: Signal processing, Noise, Filtering, Algorithms

This letter presents a self-adapting noise reduction system which is based on a 4-microphone array combined with an adaptive Wiener filter. The LMS algorithm is used for adaptation. This filtering structure allows a simple implementation in the time domain on a sample-by-sample basis.

Introduction: Speech communication is often disturbed by acoustic room noise in the speaker's environment. A microphone array with subsequent Wiener filtering can reduce the received noise signal considerably. If the desired speaker is relatively close to the microphone array (the direct sound dominates) and the noise sources are more distant to the array (the sounds reflected from the walls dominate), the speech signal is received as a correlated signal in the microphones whereas the noise signals appear to be mutually uncorrelated. This effect can be used for adapting the Wiener filter automatically.[1,2] Kaneda *et al.*[1] presented a two-microphone system with an adaptive post-filter, where the signal processing is carried out in the frequency domain using the FFT algorithm. The author[2] described an improved algorithm for a 4-microphone system, where the signal processing is again carried out in the frequency domain. In the following, an alternative system will be presented which allows a very simple implementation in the time domain.

Noise reduction system: The noise reduction system (Fig. 1) is based on a microphone array with four microphones $M_1, \ldots, M_4$. The beam steering unit consists of four time delays $T_1, \ldots, T_4$, which are adjusted such that the desired speech signal s arrives simultaneously in the four delay-compensated signals

$$x_i = s + n_i \qquad i = 1, \ldots, 4 \quad (1)$$