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MBE-GROWN InGaAlAs 1·5 μm MQW RIDGE WAVEGUIDE LASER DIODES WITH AlAs ETCH STOP LAYERS

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Ridge waveguide multiple quantum well laser diodes in which the ridge heights are predetermined by etch stop layers have been fabricated for the first time in InGaAlAs materials lattice-matched to InP. A 3 nm thick pseudomorphic AlAs layer forms the etch stop layer in these devices and the selective etching was performed by a succinic acid solution that etches InGaAs and InAlAs but not AlAs. With this technique, more reliable and uniform ridge stripe device fabrication is expected.

Recently, there has been a growing interest in quantum well laser diodes based on the InGaAlAs material system for optical communication applications [1]. InGaAlAs-based quantum wells are expected to have an advantage over InGaAsP-based quantum wells due to their larger conduction band offset. In fabricating ridge waveguide laser devices, accurate control of the ridge height is extremely important, and the technique of using an etch stop layer with suitable selective etching is attractive. Such a technique has been tried for InGaAsP ridge waveguide devices with a mixture of H_3PO_4 and HCl acids selectively etching InP top cladding over InGaAsP separate confinement layers [2], and for GaAs-based devices with an AlAs etch stop layer and a succinic acid solution [3]. In this Letter, we demonstrate that a technique similar to that used by Elman *et al.* [3] with GaAs-based devices can be used for laser devices based on MBE-grown InGaAlAs heterostructures lattice-matched to InP.

Fig. 1 shows the layer structure used for this work. A 1 μm thick Si-doped ($n = 5 \times 10^{17}\,\text{cm}^{-3}$) $In_{0.52}Al_{0.48}As$ layer was first grown on an n^+ InP substrate. A 0·18 μm thick graded-index separate confinement heterostructure (GRINSCH) layer was then grown in which the material composition was continuously graded from $In_{0.52}Al_{0.48}As$ to the quaternary $In_{0.52}Ga_{0.24}Al_{0.24}As$ using a computer controlled graded layer growth technique [4]. The active region contains five 9·5 nm $In_{0.53}Ga_{0.47}As$ quantum wells separated by 8·0 nm thick $In_{0.52}Ga_{0.24}Al_{0.24}As$ barriers. The top GRINSCH region is symmetric to the bottom GRINSCH region. No intentional doping was carried out for the GRINSCH and active regions. Immediately after the top GRINSCH region, a 3 nm thick Be-doped ($p = 10^{18}\,\text{cm}^{-3}$) AlAs etch stop layer was grown. A 2 μm thick Be-doped ($p = 5 \times 10^{17}\,\text{cm}^{-3}$) InAlAs top cladding layer was then grown. Finally, a 100 nm thick p^+ $In_{0.53}Ga_{0.47}As$ contact layer was grown with a Be concentration of $5 \times 10^{19}\,\text{cm}^{-3}$.

During growth, the substrate temperature was regulated to around 530°C for the InAlAs layers, 510°C for the quantum wells and barriers, GRINSCH regions and the etch stop layer, and 400°C for the p^+ InGaAs contact layer. The arsenic beam equivalent pressure was maintained at around 10^{-5} torr

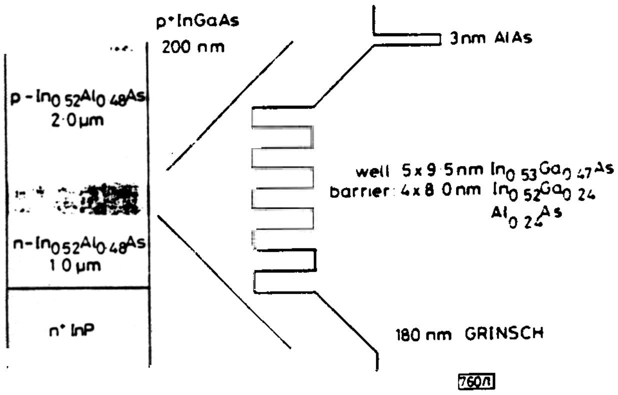

Fig. 1 *Layer structure for InGaAs/InGaAlAs GRINSCH MQW laser diode with AlAs etch stop layer*

throughout the growth. The growth was performed without any interruption by using two separate gallium cells for well and barrier layers. The lattice mismatch in each layer is estimated to be less than ±0·1% by X-ray diffraction measurement.

The etch stop layer was placed between the top cladding and GRINSCH layers so that maximum current and lateral optical confinements were achieved, but it could equally well have been placed at any desired location. In our experience of growing AlAs layers on InP, the thickness of 3 nm is below the critical layer thickness for strain relaxation under the above-mentioned growth condition. No material quality degradation due to the strained AlAs layer was observed from *in situ* monitoring of RHEED, nor from X-ray and photoluminescence characterisations.

After the growth, the ridge waveguide devices were fabricated in the following steps. Stripes of various width were first formed by etching two parallel channels next to the stripe. The etching was performed first with a 5 : 1 : 1 mixture of DI water, phosphoric acid (H_3PO_4) and hydrogen peroxide (H_2O_2), which etches InAlAs with the etch rate of 1 μm/min. The duration of etching was carefully timed so that the bottom of the etched channel was approximately 150 nm above the etch stop layer. Immediately after this etching, the sample was immersed into the selective solution until the AlAs layer was exposed. The selective etching solution was made up of 15 parts succinic acid solution (200 g of succinic acid in 1 l of DI water) and 1 part hydrogen peroxide. The pH of the solution was regulated to the value of 4·2 by adding ammonium hydroxide (NH_4OH). The etch rate of InAlAs in this solution is ~60 nm/min and it takes more than 25 min for this etchant to break through the 3 nm thick AlAs etch stop layer [5]. The etching was performed in two steps since the etch rate of the selective etching solution was too slow to etch the entire top cladding layer by itself. The selective etching process was monitored by periodically inspecting the sample under the microscope, the slight roughness caused by the heavy Be doping on the top surface is maintained during the etching until the shiny AlAs layer is completely exposed, at which point the etching can be terminated. It was found, however, that the selective etching solution did not etch InAlAs very well if the sample was exposed to the air for long during the microscopic inspection. The cause of this is believed to be the surface oxidation of the exposed InAlAs that is not readily removed by the selective etching solution. Consequently, the best results were obtained if the exposure of the sample to the air during the selective etching process was minimised. After the selective etching, 200 nm thick PECVD SiO_x was deposited and contact openings were made on the stripes. Cr/Au was then sputtered for *p*-side metallisation. After backside lapping and AuGe evaporation, the sample was cleaved into bars of different lengths and then cut into individual devices for characterisation.

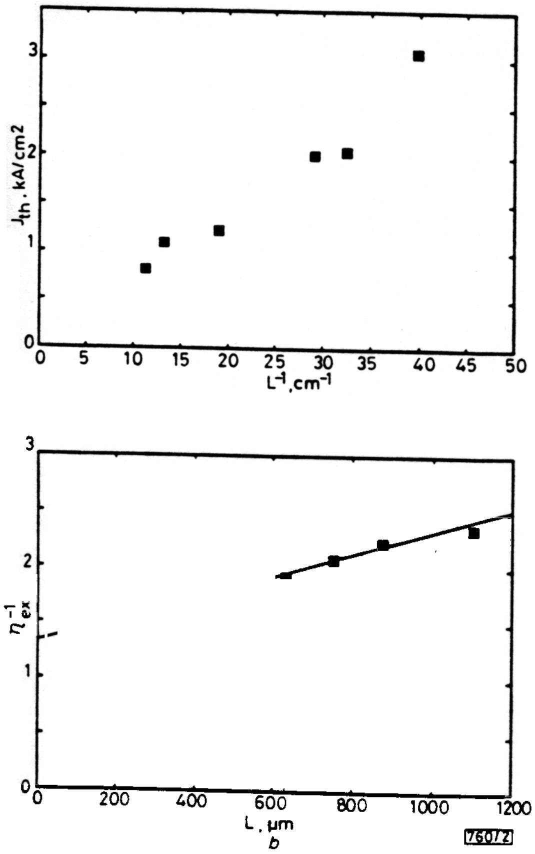

Fig. 2 *Dependence of threshold current density and external quantum efficiency on cavity length for broad area devices*

a Threshold current density
b External quantum efficiency $\eta_i = 0{\cdot}75$, $\alpha = 13\,\mathrm{cm}^{-1}$

Fig. 2 shows the cavity length dependence of threshold current densities and external quantum efficiencies for 100 μm wide broad area devices under pulsed current excitation. Each data point was obtained by measuring 5–10 different devices with the same cavity length and taking the best value. The lowest threshold current density achieved was 860 A/cm² for the cavity length of 865 μm. The estimated internal quantum efficiency is 0·75 and the loss $13\,\mathrm{cm}^{-1}$. Fig. 3 shows the light output power against current for a 3 μm wide ridge waveguide device with a cavity length of 290 μm under pulsed current excitation. The device lases at 30 mA and has a slope efficiency of ~21% for a facet. It has a lasing wavelength of 1·52 μm and a far field full width at half maximum of ~15°. All the characterisation was performed at room temperature with 200 ns wide current pulses under non-packaged probing contacts.

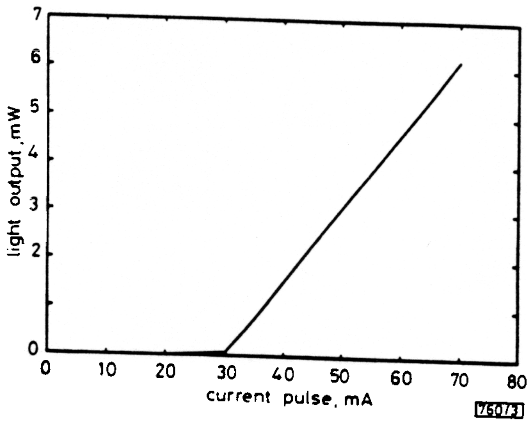

Fig. 3 *Light output against pulsed current*

$3 \times 290\,\mu m^2$, $I_{th} = 30\,mA$, $\eta = 21\%$

In summary, we have successfully used AlAs etch stop layers and succinic acid-based selective etching solutions to fabricate ridge waveguide InGaAlAs/InP laser diodes in which the ridge height is accurately controlled to a predetermined value. This development should improve the process reliability and device uniformity by precisely controlling the stripe height which in turn determines the current confinement and the optical mode profile.

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