waveguide layer thickness change of only 65 Å, or a compositional change to shift the luminescence wavelength of this layer by only 74 Å.

In addition to the crystal uniformity, both the weaker guiding in the Bragg region and the passive nature of the Bragg medium also contribute to the wavelength uniformity. The perturbations in the passive guide mentioned above have significantly less impact on the lasing wavelength than similar perturbations in the active layer of a distributed feedback (DFB) laser would have. For example, the same 65 Å or 74 Å changes in thickness or luminescence, respectively, if occurring in an active layer of a typical DFB structure, would result in a wavelength change of 13 Å compared to the 2·7 Å for the DBR laser. This reduced sensitivity of the DBR results primarily from the weaker index step in the passive guide. In addition to this reduced sensitivity, the DBR wavelength is also unaffected by changes in threshold gain of the structure. DFB laser wavelengths are affected to some degree by threshold gain variations due to the carrier density dependence of the refractive index. Facet cleave effects often produce such variations in threshold gain, and also tend to place the lasing mode in a range of positions across the stopband, which itself often exceeds 20 Å.

The practical consequences of such wavelength uniformity are significant. In the example studied here, any laser from this wafer can be used for heterodyne detection of any other laser from the wafer with only some minor temperature tuning. For WDM or filtering applications, any designed spectral shifts would reliably maintain their values across the entire wafer.

In summary, we have demonstrated exceptional wavelength uniformity in 1·3 μm GaInAsP/InP SIPBH-DBR lasers with base wafers grown by CBE and MOCVD regrowth. We believe this indicates the desirability of DBR lasers and beam/vapour growth technologies for applications requiring tight spectral control of semiconductor lasers. The authors would like to acknowledge R. S. Tucker for providing the small-signal modulation response data.

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GaInAsP/InP SINGLE-QUANTUM-WELL (SQW) LASER WITH WIRE-LIKE ACTIVE REGION TOWARDS QUANTUM WIRE LASER

Indexing terms: Semiconductor lasers, Quantum optics, Epitaxy

Lasing operation of a GaInAsP/InP single-quantum-well laser with very narrow (0·12 μm) wire-like active region was obtained for the first time under CW condition at 77 K. It was fabricated by a two-step organometallic vapour phase epitaxy (OMVPE) and wet chemical etching process. The threshold current density of the laser was 810 A/cm^2. This lasing operation with such a narrow active region indicates that the technique employed here would be suitable for realising a higher-dimensional quantum-well laser, such as quantum wire and box lasers.

Introduction: Multidimensional quantum-well lasers are very attractive for the excellent characteristics such as superior temperature dependence[1] and low threshold current[2] compared with conventional one-dimensional quantum-well lasers.

We have reported light emission by current injection from a quantum-box structure at 77 K.[3] However, in this structure, lasing operation was not obtained because the optical confinement factor was quite small, owing to a large spacing between the quantum boxes (204 nm) compared to their size (30 nm).

In this letter we report the lasing operation of a GaInAsP/InP SQW laser with a wire-like active region 0·12 μm wide. The laser was fabricated by a two-step OMVPE growth and wet chemical etching process. Special attention was paid to the damage during the fabrication process, to establish it for multidimensional quantum-well structures such as quantum wire or quantum box lasers.

Fabrication process: A schematic view of the GaInAsP/InP wire structure laser is shown in Fig. 1. The wire-like active region was embedded between InP layers, and the *pn* junction was formed just at the bottom of the active region. A GaInAsP waveguide layer was provided under these wires to enhance the optical confinement into the active region, as well as to guide the light. The sample was fabricated from a two-step OMPVE growth and wet chemical etching process as explained below.

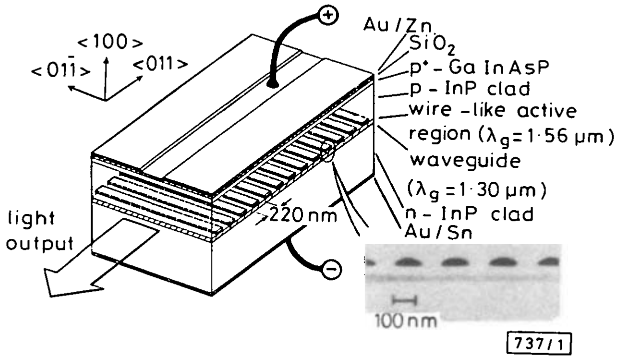

Fig. 1 *Schematic view of laser with wire-like separated active regions*

First, the GaInAsP/InP wafer with a single quantum well structure, consisting of an *n*-InP buffer layer (2 μm-thick), an *n*-GaInAsP waveguide layer ($\lambda_g = 1{\cdot}30\,\mu$m, 50 nm), an *n*-InP barrier layer (20 nm), an undoped GaInAsP quantum-well layer ($\lambda_g = 1{\cdot}56\,\mu$m, 30 nm), and a *p*-InP top layer (20 nm), was grown on an n^+-InP substrate by low-pressure OMVPE.[4]

The wafer then underwent a mesa etching process using the holographic lithography technique and successive wet chemical etching.[3] A thin InP top layer was used as a mask and also for protecting the surface of the active layer from thermal degradation during the following embedding growth.

Then the wire-like active layer was buried with a *p*-InP cladding layer (2 μm-thick) and a p$^+$-GaInAsP cap layer (0·2 μm) by OMVPE at 600°C. As can be seen in the SEM cross-sectional view of the regrown wafer shown inset in Fig. 1, the active region was completely separated into wires 30 nm thick and 120 nm wide.

Finally, electrodes were formed perpendicular to the wires for current injection with 20 μm SiO_2 stripe windows.

Results and discussion: We checked the crystal quality of the wafer, which is an important factor in deciding lasing operation before and after regrowth, by the photoluminescence (PL) intensity. The problem faced during LPE regrowth[3] was the drastic decrease, i.e. one order of magnitude, in PL intensity. The reason for this was the thermal damage caused to the active layer because of the high soak temperature (640°C) at which the wafer was held to facilitate mass-transport. With the OMVPE regrowth at 600°C, the PL intensity decreased to only half or one-third of that after grating formation.

CW operation of the laser with a cavity length of 390 μm at 77 K was obtained, and the I/L characteristic is shown in Fig. 2. The threshold current and threshold current density

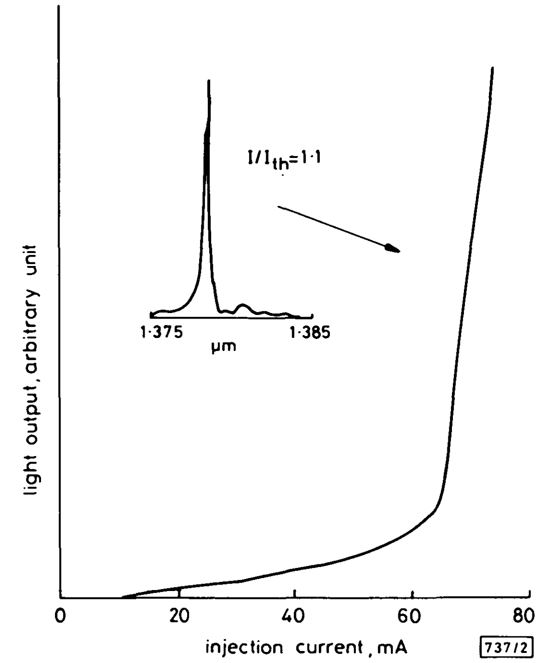

Fig. 2 *I/L characteristic for CW operation at 77 K*

were 63 mA and 810 A/cm^2, respectively. These values are 2·6 times the theoretical values.[5] The calculation indicates that much lower threshold current density can be obtained by increasing ξ up to several per cent by adopting an MQW (a few pairs) structure or by reducing the space between the wire-like active regions. We believe that the quality of the fabricated wire-like active region is quite good, and that the present fabrication process is suitable for much narrower wire-like patterns, such as quantum wire and quantum box lasers.

The spontaneous emission spectra below the threshold are shown in Fig. 3. There are several peaks, among which that corresponding to 1·38 μm becomes the lasing one. The wave-

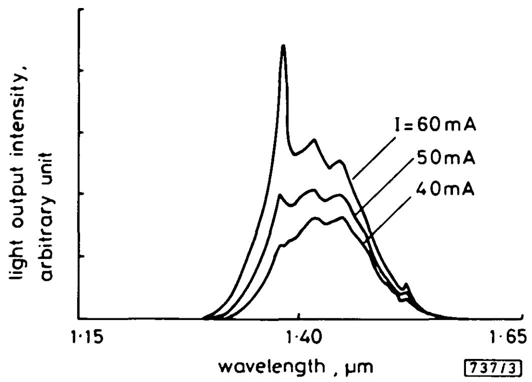

Fig. 3 *Spontaneous emission spectra below threshold at 77 K*

length difference between these peaks was much larger than the resonant mode spacing of 0·7 nm defined from the cavity length. In fact, all these peaks correspond to the gain peaks calculated from a 30 nm-thick quantum-well structure, and the lasing wavelength is equal to that of the fourth quantum level. This confirms the one-dimensional quantum-well effect in this structure; however, the quantum wire effect was not confirmed because the width of wire was quite large.

A small peak appears at 1·52 μm, which corresponds to the Bragg wavelength of the period of the wires. By adjusting the wavelength of the gain peak to the Bragg wavelength, a kind of DFB laser which has a periodic gain structure[6] can be realised. In such a structure, stable single-mode operation can be obtained without a $\lambda/4$ shift region.

Conclusion: A GaInAsP/InP single-quantum-well (SQW) laser with very narrow wire-like active region was fabricated for the first time by an all-OMVPE growth process, and CW operation was obtained at 77 K. This successful lasing proved that good crystal quality of active region was obtained after wire fabrication and OMVPE regrowth. This method can thus be used effectively for fabricating multidimensional quantum-well lasers.

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Erratum

AL-HUSSAINI, E.K.: 'Performance of mean-level detector in presence of multiple-tone interference plus noise', *Electron. Lett.*, 1988, **24**, (10), pp. 643–645

A number of errors occurred during the printing process, and should be corrected as follows:

(*a*) In eqn. 1, α^u should read αu

(*b*) In the first line of eqn. 6, the term $(-1)^{k_l k-1}$ should instead read $(-1)^k l^{k-1}$

(*c*) Throughout the published paper, α_z should read αz

(*d*) In eqn. 11 in the Appendix, the term $\exp[\alpha_{lz}/(1-\alpha_z)]$ in the second line should instead read $\exp[\alpha lz/(1-\alpha z)]$