Semiconductor Quantum Well Lasers With a Temperature-Insensitive Threshold Current

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Abstract—This paper proposes and demonstrates a new multi-quantum well (MQW) laser structure with a temperature-insensitive threshold current and output power. Normally, the mechanisms that cause the threshold current (I_{th}) of semiconductor lasers to increase with increasing temperature T (thermal broadening of the gain spectrum, thermally activated carrier escape, Auger recombination, and intervalence band absorption) act together to cause I_{th} to increase as T increases. However, in the design presented here, carriers thermally released from some of the QWs are fed to the other QWs so that these mechanisms compensate rather than augment one another. The idea is in principle applicable to a range of materials systems, structures, and operating wavelengths. We have demonstrated the effect for the first time in 1.5 μm GaInAsP/InP Fabry–Perot cavity edge-emitting lasers. The results showed that it is possible to keep the threshold current constant over a temperature range of about 100 K and that the absolute temperature over which the plateau occurred could be adjusted easily by redesigning the quantum wells and the barriers between them. TEM studies of the structures combined with measurements of the electroluminescent intensities from the wells are presented and explain well the observed effects.

Index Terms—Diode lasers, quantum well, temperature dependence, thermal stability.

I. INTRODUCTION

QUANTUM well (QW) lasers have been extremely successful in a wide range of applications, with optical fibre communications being of particular importance. However, in spite of their success, their performance is not ideal [1], [2]. For example, the threshold current of semiconductor lasers is often very sensitive to temperature due to various processes depending on the operating wavelength [1]–[10]. As a result, around

80% of electrical power is wasted in a 1.55 μm InGaAsP laser chip as heat [8]. This has led to the need for thermoelectric coolers and associated control electronics to stabilize the laser temperature. However, such coolers often consume more energy than the laser they are controlling and also add to the overall heat dissipation of the system. Such coolers also tend to have far less long-term reliability than the laser diode itself. There are consequently many circumstances where it would be advantageous and far cheaper to simply compensate for temperature variations by mechanisms built into the epitaxial structure of the laser chip itself. This paper focuses on a new design and demonstration of a MQW laser structure which can overcome the intrinsic temperature sensitivity of the threshold current of QW lasers.

There are several mechanisms that may cause the threshold current (I_{th}) of semiconductor lasers to increase rapidly with increasing temperature, T [1], [2]. These include thermal broadening of the gain spectrum leading to increase in the radiative current with increasing T [1], thermally activated carrier escape from the QWs [4], [5], Auger recombination [1]–[8], [11] and inter-valence band absorption [1], [7], [12], [13]. Normally all of these processes act together to cause I_{th} to increase as T increases. To compensate for the temperature dependence of GaInAs MQW lasers, approaches involving in-built stress have been attempted (characteristic temperature of I_{th} , T_0 , was improved from 51 to 133 K at 293 K $< T < 343$ K) [16], [17] although these have required significant changes to the standard laser fabrication process. In strongly inhomogeneous systems like self-assembled quantum dot lasers improved carrier thermalisation with increasing temperature can partly compensate for the processes which increase I_{th} leading to a temperature stable operation over a small temperature range [5], [6], [14], [15]. Here we present a novel design of QW active region [18] such that carriers released from some of the QWs are fed to the other QWs in such a way that these mechanisms compensate rather than augment one another. The idea is in principle applicable to a range of materials systems, structures and operating wavelengths. However, we chose to demonstrate the effect for the first time in 1.5 μm GaInAsP/InP edge emitting lasers, since these have been so extensively characterized and their parameters are relatively well known [1], [7].

II. DESIGN AND SIMULATION

The design concept can be most easily understood by considering Fig. 1, which shows the variation of the total bandgap with position across the structure. QWs 4, 5 and 6 (W4, W5 and W6 in Fig. 1) provide effectively the active region of a

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Fig. 1 Schematic diagram of the total bandgap in the designed structure.

compressively strained three-QW $1.5 \mu\text{m}$ laser. QWs W1–3 and W7 provide carrier traps which, being shallower than the active QWs, release their carriers by thermal excitation as the temperature increases. These released carriers can now transfer to the deeper active QWs and so provide the extra current needed as the non-radiative loss mechanisms increase with increasing temperature. As a result, the total current through the laser can be made to remain approximately constant as the temperature changes. The exact range of temperature over which this occurs depends on the number, depth and distribution of the shallower wells and also on the heights of the barriers between the wells. These are all adjustable parameters in the structure design.

With such a wide variety of parameters available to provide the required effect it was necessary first to investigate the structure theoretically. This was undertaken using LaserMOD (a Synopsys Rsoft design solution) [19] which predicted that an almost constant value of I_{th} could be achieved over more than 80 K in the range around room temperature with the bandgap alignment shown in Fig. 1. Care was also taken to maintain overall strain neutrality across the structure. Also, for simplicity of growth, the Ga and the In compositions were kept constant throughout the QWs so that all the well depths and barrier heights were determined by the As/P ratio. All the QWs were 6 nm wide while the barriers between them were 10 nm wide.

Fig. 2 shows the simulated light–current characteristics for this structure. As can be seen, not only is the threshold current constant, but also the slope efficiency. This is primarily because the total current through the device and hence the hole density remained constant as the temperature increases and so intervalence band absorption [12], the primary cause for the degradation of the slope efficiency, also remains essentially constant. As a result, the output power at a fixed current above threshold also stayed almost constant with increasing T as is shown in the inset in Fig. 2 where it is compared to the results for a standard $1.5 \mu\text{m}$ laser [20].

III. EXPERIMENTAL APPROACH

The devices were grown by metalorganic vapor phase epitaxy (MOVPE) at low pressure (80 mbar) in a commercial horizontal reactor with purified N_2 as the carrier gas. The precursors were trimethylindium (TMIn), trimethylgallium (TMGa), arsine

Fig. 2 Temperature dependence of calculated light-output characteristics of the proposed laser. Inset: temperature dependence of the calculated output power (normalized to its value near 293 K) in a standard InGaAsP/InP $1.5 \mu\text{m}$ laser (open squares) (see [20, Fig. 37.20]) and in a specially designed laser (full circles) with the same lasing wavelength fabricated according to Fig. 1. The power values were determined at a constant current of 400 mA for the modelled device.

(AsH_3), and phosphine (PH_3), with diethylzinc (DEZn), carbon tetrabromide (CBr_4) and disilane (Si_2H_6) used as dopants. Materials were grown on InP (1 0 0) perfectly oriented n-type substrates. The samples were grown at 630°C real estimated growth temperature, with growth rate (Gr) $0.8 \mu\text{m/h}$ and V/III ratio of 500 for InP [21] and growth rate $\text{Gr} = 0.95 \mu\text{m/h}$ and V/III ratio from 100 to 350 in case of different compositions of InGaAsP. All samples were characterized as grown for quality control by Nomarski interference contrast microscopy and atomic force microscopy, revealing mirror-like surfaces typical for MOVPE surface step organization. X-Ray diffraction measurements were undertaken to confirm crystallinity and to determine the lattice parameter of the grown layers. Doping levels were estimated by capacitance-voltage measurements. Devices were fabricated with 50 and $80 \mu\text{m}$ wide stripe contacts so that any temperature dependent current spreading was negligible. The devices were produced with as-cleaved facets and 1 and 1.5 mm cavity lengths.

The devices were mounted in a closed cycle cryostat with temperature control over a temperature interval of 20–300 K. The devices were operated in a pulsed regime (1 kHz frequency and 500 ns pulse width) to avoid self-heating effects. The emission from one facet was collected using a standard multimode optical fibre. To compare the temperature behavior of the emission spectra from the shallow and deep QWs, measurements were also carried out at a low continuous wave current of 50 mA ($\sim 35 \text{ A/cm}^2$) where the self-heating effect is negligible. The emission spectra in the cryostat were measured using a fibre coupled optical spectrum analyzer. Due to multimodal lasing operation and therefore variation in the collection efficiency of the light by the fibre, such arrangements are not suitable for accurate slope efficiency measurements. Therefore only the variation in threshold current could be reliably monitored in these measurements as presented in this paper.

IV. RESULTS AND DISCUSSION

The temperature dependencies of the threshold current in the fabricated devices are shown in Fig. 3. Sample “A” was the first

Fig. 3. Temperature dependence of threshold current density in two InGaAsP/InP laser structures grown according to a simulated design with predicted temperature insensitive behaviour.

to be grown and as can be seen, it displayed a constant threshold current over a range of approximately 70 K but centered at a lower temperature (80–150 K) than predicted by the simulation in Fig. 2. The device lased at $1.63\ \mu\text{m}$ at room temperature and analysis of the emission spectra showed that the growth differed significantly from the nominal design which may be due to uncertainties in both the modeling parameters and/or growth conditions. However, the fact that a region of constant I_{th} existed indicated that the concept worked in principle. Taking into account the results for sample “A”, the growth parameters were empirically adjusted and sample “B” was grown (QWs 1, 2, 3, 7: $\text{In}_{0.82}\text{Ga}_{0.18}\text{As}_{0.62}\text{P}_{0.38}$; QWs 4, 5, 6: $\text{In}_{0.82}\text{Ga}_{0.18}\text{As}_{0.68}\text{P}_{0.32}$). As can be seen the flat I_{th} region was successfully moved from low temperature and now spanned from approximately 140 to 270 K. This device lased at $1.47\ \mu\text{m}$ at room temperature indicating that the structure was still not exactly as designed. However, the changes made between sample “A” and sample “B” were well within the limits of the variations available and therefore provides confidence that further iterations would make it possible to produce a device able to work at, for example, $1.55\ \mu\text{m}$ and with a constant I_{th} at room temperature and above.

To confirm that the desired carrier transfer processes were indeed occurring, studies were made as a function of temperature of the emission from the end facet at a fixed current below threshold. The spectra observed for the two samples are shown in Fig. 4.

We consider first the results for sample “A”. As can be seen, two peaks are clearly visible corresponding to the shallow (peak S) and deep (peak D) QWs. It should be noted that there is no change in the height of peak S between 20 and 40 K at which temperatures I_{th} increases with increasing temperature. However, between 80 and 120 K there is a clear decrease in peak S as carriers escape from the shallow wells and over this range there is no change in I_{th} indicating that the carriers have transferred to the deeper wells. Above 160 K the magnitude of peak S decreases to zero, indicating that the shallow QWs had been depleted of carriers and so could no longer supply the deep QWs, so resulting in a resumed increase in I_{th} . Another significant feature is that the photon energy corresponding to peak S indicates a shallower QW than designed and partly explains why it empties at lower temperatures than intended, causing the

Fig. 4. Emission spectra at a constant low injection current (50 mA) at different temperatures, demonstrating temperature induced carrier redistribution between the shallow (S) and deep (D) QWs.

low temperature range of the plateau in I_{th} . Similar studies were made on sample “B” and are shown for comparison in Fig. 4. They showed the same effect of the decreasing height of S over the range of the plateau in I_{th} . However, this had now moved to the temperature range 150 K–250 K, supporting the above analysis of sample “A”. It should also be noted that peak S is at longer wavelengths in sample “B” corresponding to deeper wells and hence higher release temperature than in sample “A”. While the luminescence spectra only give information about the energy separations of the valence and conduction band edges, the total depth of the wells depends on the barrier heights. Further information about these is provided by the TEM studies below.

V. FURTHER ANALYSIS

To clarify that the designed effects were occurring and to help explain why they were not happening over the intended temperature range, transmission electron microscopy of the laser structures was carried out.

Thin film sections for electron microscopy were prepared using an FEI Novalab dual beam focused ion beam microscope, using Ga ions accelerated at 30 keV. The beam damage induced by the energetic Ga ions was reduced with a final stage polish of a few ion beam passes with the foil tilted to $\pm 5^\circ$ [22]. However, artefact In islands (as seen in Fig. 5) are expected to form on the surface as a result of ion beam milling [23]. The foils were examined in a Hitachi HD2300A field-emission scanning transmission electron microscope (STEM), operated at 200 keV. The STEM has three modes of imaging: Secondary-electron, transmission (bright field) and atomic contrast (high-angle annular dark field, between 80 and 250 mrad scattering semi-angle).

Fig. 5. Z-contrast image of devices “A” and “B”, showing three shallow QWs, followed by three deeper QWs (higher As content) and the final QW with the same contrast as the first three.

TABLE I
BARRIER AND QW THICKNESSES

Barrier [nm]	5.1	9.8	9.7	9.8	9.8	10.7	10.0	5.0
QW [nm]	6.1	6.1	6.0	6.3	6.0	6.0	6.0

Fig. 6. An integrated Z-contrast intensity profile across the devices “A” and “B” (integrated over 140 nm-wide portion of the device (see Fig. 5)).

Z-contrast (where Z is the atomic number) imaging does not have diffraction contrast, so the intensity is proportional to the thickness, the density of the material and Z^2 . That is, a feature in Z-contrast appears brighter if it is thicker, denser, and much brighter if it has a higher atomic number, which means that for a flat or wedge sample, changes in contrast are directly related to changes in the density and the composition of the material, allowing for some qualitative interpretation of doping profiles.

Fig. 5 shows a higher resolution Z-contrast image of the lasing structures, with the SCH layers measuring 120 nm, with bright spots where In islands form during ion-beam milling. Table I summarises the barrier and QW measured thicknesses, from top to bottom, with 0.2 nm standard deviation, indicating that they are very close to the design.

Fig. 6 shows diagrammatically the variation of Z , the As/P ratio, across the structure as derived from the results shown in Fig. 5. Because, in general, alloys containing a higher fraction

of atoms with a high atomic number have a smaller bandgap, the variation in Z reflects the inverse of the variation in bandgap.

In other words, Fig. 6 is a reflection of the designed structure shown in Fig. 1. Broadly speaking this appears to be correct. However, several interesting features are apparent. The QWs are numbered 1 to 7 in Fig. 6, 1 being nearest to the surface. We are considering first the results for sample “A.” Well 7 appears to have a smaller As concentrations than QWs 1–3, whilst QWs 4–6 have an increased As concentration, where QW 4 appears slightly higher than QWs 5 and 6. We also note that the barriers between QWs 3–6 do not seem to fall in intensity to the levels of the barriers between QWs 1–3 and 6–7. This indicates that the barriers between these QWs were not as high as intended and this is almost certainly a further reason for the low temperature of the plateau in I_{th} . The large difference between the peaks in the Z values between the shallow and deep QWs is consistent with the large energy separation between the emission peaks in Fig. 4. Considering now the results for sample “B” we see first that the Z values (As content) in the shallow wells (1–3 and 7) are much closer to the Z value in the deep wells explaining the longer wavelength peak S in sample B. Secondly, we see that the value of Z in all the barrier regions falls well below the Z value in the outlying SCH regions and designed in Fig. 1. Thus we have higher barriers and so deeper wells so explaining the move of the plateau in I_{th} to higher range of T than in sample “A”.

In summary, information about the variation of well depths and barrier heights obtained from TEM studies when added to the results of the luminescence measurements seem to explain very well the observed plateaus in I_{th} observed and the change in temperature range between samples “A” and “B”. Because there is such a range of further well depths and barrier heights possible from the alloys available, we can be confident that further adjustments can move the plateau to room temperature and above as predicted by the structure shown in Fig. 1.

VI. CONCLUSION

We have modelled theoretically and demonstrated experimentally a new design of QW structure in which the threshold current is insensitive to temperature changes over a range of approximately 100 K. The modelling indicates that the output power of these devices would also be constant at a fixed current. Analysis of the emission spectra from the device indicates that the desired transfer of charge is indeed occurring. Also the discrepancies seen in the spontaneous emission peak energies combined with TEM studies, explain qualitatively why these initial devices show the effects at temperatures below room temperature as was intended in the design. Further steps are now planned to extend these preliminary growths to move the plateau in I_{th} to room temperature and above and to study variations in slope efficiency and output power. The generic design approach we have taken and applied to 1.5 μm devices is equally applicable to 1.3 μm lasers as well as shorter wavelengths and to mid-infrared devices in both edge-emitting and vertical cavity geometries. What is more, the structures can be grown using standard MOVPE or MBE techniques on the same cost basis as conventional devices. We therefore believe that the new design has wide applicability

for the simplification of a variety of semiconductor laser based systems leading to significant energy and cost savings.

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