Carrier leakage suppression utilising short-period superlattices in 980 nm InGaAs/GaAs quantum well lasers

D. Lock^{*,1}, S. J. Sweeney¹, A. R. Adams¹, S. Deubner², F. Klopff², J. P. Reithmaier², and A. Forchel²

¹ Advanced Technology Institute, University of Surrey, Guildford, Surrey, GU2 7XH, UK

² Institute of Physics, University of Würzburg, Am Hubland, 97074 Würzburg, Germany

Received 1 July 2004, revised 16 August 2004, accepted 18 August 2004

Published online 27 October 2004

PACS 42.55.Px, 72.20.Jv, 78.45.+h, 78.67.Dc, 85.35.Be

Short-period Super Lattices (SSLs) have been proposed as a method of reducing carrier leakage in semiconductor lasers. SSLs increase the carrier confinement by increasing the effective barrier height due to the carriers being “reflected” from the SSL. Thermionically driven leakage of electrons from the quantum wells has been suggested as an important non-radiative current path in (Al)GaAs based devices which is exacerbated at high temperatures. Due to the fact that the application of high pressure causes a reduction in the zone centre Γ -X minima splitting, pressure can be used to investigate the extent to which such leakage increase the threshold current. In this study, we compare devices with and without SSL layers and find direct evidence for leakage suppression in devices containing SSLs up to a temperature of 60 °C.

© 2004 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

980 nm quantum well semiconductor lasers are important for numerous applications. These include optical communications where they are used in Erbium doped fibre amplifiers for signal regeneration and also for medical applications such as photocoagulation, skin treatment and surgery.

Although 980 nm lasers have been produced for many years there is still some controversy concerning their poor temperature stability over the normal operating temperature range (20 °C – 80 °C). The temperature stability of a device is described by a “characteristic temperature”, T_0 , which at room temperature, RT, for an “ideal” device would be 300 K at room temperature. Most commercial 980 nm devices have a $T_0 < 200$ K and the origin of this is the subject of strong debate and has been attributed to mechanisms such as Auger recombination [1] whilst others [2, 3] have suggested that 980 nm devices suffer from thermally activated leakage of electrons from the quantum wells into either the barrier layers and/or into the X-minima of the AlGaAs cladding layers, giving rise to increased threshold currents (I_{th}), and poor temperature stability [4, 5].

The insertion of short-period super lattices (SSL) into the barrier region has been claimed to increase the effective barrier height to electrons by ~100 meV [6] and hence decrease losses from leakage and improve the T_0 . However, to date there has been no direct experimental evidence confirming that they are useful in suppressing electron leakage.

The application of hydrostatic pressure to III–V semiconductors leads to an increase in the direct band gap ($\Gamma_c - \Gamma_v$) whilst the indirect X-minima to zone centre gap ($X_c - \Gamma_v$) decreases under pressure. The net result of this movement is a decrease in the conduction band Γ to X minima separation ($X_c - \Gamma_c$) with increasing pressure. By decreasing $X_c - \Gamma_c$ we increase the probability of thermal leakage of electrons

* Corresponding author: e-mail: daren.lock@surrey.ac.uk, Phone: +44 (0) 1483 689403, Fax: +44 (0) 1483 689404

Fig. 1 (online colour at: www.pss-b.com) Diagram of band movement under pressure. $\Gamma_c - \Gamma_v$ increases whilst $X_c - \Gamma_v$ and the relative change between $X_c - \Gamma_c$ decrease.

into the X-minima (see Fig. 1). Therefore, by measuring the threshold current as a function of pressure we can accurately determine the fraction of leakage occurring within the device at laser threshold under ambient conditions.

It follows therefore that by applying this pressure measurement technique to devices grown with an SSL and comparing the results to those of “standard” QW devices, we are able to determine the effectiveness of the introduction of SSLs in with respect to suppressing electron leakage.

2 Pressure and temperature dependence of current paths

In the absence of non-radiative current paths such as defect-related recombination and Auger recombination, the threshold current, I_{th} , may be written in terms of two current paths where, $I_{th} = I_{rad} + I_{leak}$, where I_{rad} is the radiative recombination current (due to spontaneous emission) and I_{leak} is the current contribution due to carrier leakage. In an ideal QW laser [7], $I_{rad} \propto T$, therefore if the threshold current is entirely radiative, we can express the threshold current as $I_{th} \propto T$. Furthermore, I_{rad} has the ideal band gap (E_g) dependence [8] of $I_{rad} \propto E_g^2$. Thus, by applying pressure, we would expect to observe an increase in the radiative current, and hence in the threshold current. Leakage into the X-minima however increases strongly with increasing pressure and temperature and hence, at a fixed temperature it will cause an increase in threshold current with increasing pressure. The amount by which I_{th} increases will depend on the extent to which it contributes to the threshold current. The increase of I_{leak} into the X-minima is described by

$$I_{leak} = I_0 \exp \left(- \frac{d(\Delta E)}{dP} \frac{P}{kT} \right), \quad (1)$$

where I_0 is a constant, k is the Boltzmann constant, T is the absolute temperature and P is the pressure. ΔE is equal to the energy separation between the electron quasi-Fermi level and the energy of the lowest X-minima. In the absence of optical loss, at threshold, the quasi-Fermi-level lies at approximately the same energy as the electron ground-state, and hence, has the same pressure dependence as the direct optical gap. It can be seen from Fig. 1 that as pressure increases, ΔE ($\approx X_c - \Gamma_c$) decreases leading to an increase in I_{leak} . By measuring the lasing wavelength as a function of pressure we can determine the pressure dependence of I_{rad} . Furthermore, given that the rate at which ΔE changes with pressure is well known ($d\Delta E/dP = -12.4$ meV/kbar [9]) we also know how I_{leak} increases with pressure. Thus, from measurements of the pressure dependence of the threshold current, we can determine the extent to which each of the current paths contributes to I_{th} .

3 Experimental studies

For this study we considered two types of 980 nm QW lasers. The first set of devices, hereafter referred to as “standard”, are commercially grown double QW devices consisting of compressively strained

InGaAs QWs within GaAs barriers and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ cladding layers. The second set of devices, hereafter referred to as “SSL”, contains almost exactly the same active region as the standard structures but with an additional AlGaAs Short-period Super Lattice (SSL) grown between the GaAs barrier layers and the AlGaAs cladding. Further details of the samples can be found in [6]. The devices were cleaved into individual laser chips with uncoated facets.

The devices were mounted on a piston in cylinder, hydrostatic pressure system with electrical and optical feed-throughs. The electrical feed-throughs are provided by conical pins in the piston, sealed and insulated with Vespel seals. The lasers are driven with a pulsed current source with pulse widths of 500 ns at a repetition frequency of 10 kHz. This minimises current heating effects in the devices. The optical feed-through is provided by a standard multi-moded silica fibre which is glued into a stub and sealed onto the end of the piston. The fibre allows the transmission of the lasing light out of the pressure system and is terminated with a standard optical fibre adapter to allow straightforward connection to an optical spectrum analyser (to measure the wavelength) and optical power meter (to measure the light output). The threshold current is determined from the light-versus current characteristic at each pressure. The piston is placed inside the cylinder with an “Essence F” liquid pressure medium. A variable force of up to 120ton is applied to the piston enabling a maximum operating pressure of 15 kbar. The pressure is determined by measuring the resistance of a Manganin wire coil which has a well pressure dependent resistivity.

4 Results and discussion

In order to measure the increase of direct band gap as a function of pressure, the wavelength of both sets of devices was measured, from which we extract the lasing energy, E_{lase} . Figure 2 shows the change in lasing energy as a function of pressure for both the standard and the SSL devices. We observe an almost identical pressure dependence of $\approx 9.5 \text{ meV kbar}^{-1}$ for the two devices because the QWs are nominally identical. Due to the fact that the lasing energy closely follows the band gap, we use it to calculate the pressure dependence of the radiative current, E_g^2 .

In Fig. 3 we plot the relative change in I_{th} and I_{rad} (from E_{lase}^2) for both the standard and SSL devices as a function of pressure at RT. we observe that up to $\sim 8 \text{ kbar}$ both devices behave ideally, ($I_{\text{th}} = I_{\text{rad}}$). However, for the standard devices, we observe a strong increase in I_{th} above 8 kbar, consistent with X-minima leakage. From this measurement, by considering the relative contributions of the radiative and leakage currents, we estimate that carrier leakage accounts for 0.1% of I_{th} at room temperature and atmospheric pressure (RTP). In contrast, for the SSL devices I_{th} increases slowly and steadily due to the pressure dependence of the radiative current alone, indicating that carrier leakage is not occurring. By increasing the temperature, the probability of leakage also increases (as can be seen from Eq. (1)). A ‘thermal’ jacket is placed around the pressure cylinder and heated up to 60°C in order to raise the tem-

Fig. 2 (online colour at: www.pss-b.com) Lasing energy as a function of pressure for both the SSL (squares) and the standard (circles) devices. The rate of increase of lasing energy with pressure for both sets of devices is approximately the same at 9.5 meV/kbar consistent with the pressure dependence of the band gap.

Fig. 3 (online colour at: www.pss-b.com) Pressure variation of the threshold current at 20 °C, as a function of pressure for both the SSL and standard structures. It can be observed that the standard exhibits signs of leakage at this temperature whilst the SSL remains “ideal”.

Fig. 4 (online colour at: www.pss-b.com) Pressure variation of the threshold current at 60 °C, as a function of pressure for both the SSL and standard structures. Even at high temperatures the SSL still exhibits no sign of leakage.

perature of the entire system. The temperature is monitored using a thermocouple. Also, as the devices have a well known temperature dependence of the lasing wavelength, it is easy to double check the temperature of the system from the wavelength shift. In Fig. 4 we can observe the threshold current for both the standard and the SSL structure at 60 °C. As can be seen the fraction of carriers leaking into the X-minima has increased to 0.5% at RTP for the standard structure, whilst it can be seen clearly that the SSL structure remains ideal even at elevated temperatures.

The effect of increasing the temperature on carrier leakage is perhaps clearer in Fig. 5, where the threshold current for the standard devices at 60 °C can be observed to become important at a lower pressure than at 20 °C. In contrast, Fig. 6 shows a comparison of the SSL device at both temperatures measured where it can clearly be seen that there is no discernable difference between the two temperature measurements indicating that the Short-period Super Lattice is indeed suppressing carrier leakage across the barriers.

Fig. 5 (online colour at: www.pss-b.com) Increase in leakage with temperature can clearly be seen by the increase in threshold current at 60 °C for the standard devices. Leakage becomes more important at a lower pressure when the temperature is raised to 60 °C.

Fig. 6 (online colour at: www.pss-b.com) Pressure variation of the threshold current at 20 °C and 60 °C, as a function of pressure for the SSL structure. From this data, there is no evidence of carrier leakage, in contrast to the standard devices.

5 Conclusion

We have shown that hydrostatic pressure is an invaluable tool in determining the recombination mechanisms present within semiconductor lasers. In particular we have applied the measurements to assess the effectiveness of introducing short-period super lattices into the growth structure in order to reduce thermally activated electron leakage out of the QW. From our experiment we observe that whilst the lasing energy dependence on pressure is nominally identical for the two structures, the behaviour of the threshold current is quite different. From measurements of the threshold current carried out at 20 °C, we find no evidence of carrier leakage in the SSL devices. In contrast, for the standard structure we see leakage effects under pressure. At elevated temperatures (60 °C) carrier leakage increases in the standard devices becoming more significant at a lower pressure compared to the 20 °C measurement. In contrast, for the SSL devices we find that even under high pressure and at temperature there is no evidence of carrier leakage. These results therefore provide the first direct experimental verification of the effectiveness of short-period super lattices in suppressing electron leakage and has implications for future laser design where carrier leakage may be important.

Acknowledgements The authors wish to thank EPSRC (UK) and Bookham for supplying a studentship for one of us (DL).

References

- [1] D. Lock, S. J. Sweeney, A. R. Adams, and D. J. Robbins, *phys. stat. sol. (b)* **235**(2), 542–546 (2003).
- [2] S. Y. Hu, S. W. Corzine, Z. M. Chuang, K.-K. Law, D. B. Youing, A. C. Gossard, L. A. Coldren, and J. L. Merz, *Appl. Phys. Lett.* **58**, 1125 (1991).
- [3] J. K. Wade, L. J. Mawst, and D. Botez, *Appl. Phys. Lett.* **71**, 172 (1997).
- [4] S. J. Sweeney, G. Knowles, T. E. Saleand, and A. R. Adams, *phys. stat. sol. (b)* **223**, 567 (2001).
- [5] H. Page, A. T. Meney, A. R. Adams, and C. J. Vand der Poel, *phys. stat. sol. (b)* **211**, 533 (1999).
- [6] F. Shafer, B. Mayer, J. P. Reithmaier, and A. Forchel, *Appl. Phys. Lett.* **73**(20), 2863 (1998).
- [7] A. F. Phillips, S. J. Sweeney, A. R. Adams, and P. J. A. Thijs, *IEEE J. Sel. Top. Quantum Electron.* **5**(3), 401 (1999).
- [8] S. J. Sweeney, G. Knowles, T. E. Sale, and A. R. Adams, *phys. stat. sol. (b)* **223**, 567 (2001).
- [9] P. Bhattacharya, *Properties of Lattice-Matched and Strained Indium Gallium Arsenide* (IEE/Inspec, London, 1993).