Recombination mechanisms in InAs/InP quantum dash lasers studied using high hydrostatic pressure

I. P. Marko^{*1}, S. J. Sweeney¹, A. R. Adams¹, S. R. Jin¹, B. N. Murdin¹, R. Schwerberger², A. Somers², J. P. Reithmaier², and A. Forchel²

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

² Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

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Two types of InAs quantum dash lasers grown on InP substrates with lasing wavelengths of 1.52 μm and 1.76 μm were studied. In both laser types the threshold current density, J_{th} , was about 2 kA/cm^2 at room temperature and had a similar temperature sensitivity (T_0 was about 80 K in the range $T = 120$ –250 K, and $T_0 = 60$ –70 K from 250 to 300 K). Measurements of the spontaneous emission from a window milled in a substrate contact showed that J_{rad} , the radiative part of J_{th} , is almost temperature independent and less than 5% of J_{th} at $T = 295$ K, demonstrating that the relatively large value of J_{th} and its temperature sensitivity must be due to non-radiative recombination processes. However, despite the similar temperature behaviour of the lasers, their pressure dependences were very different showing that in the 1.52 μm lasers, pressure independent defect related recombination outside the dashes due to thermal carrier spill-over or thermal leakage dominates, while in the 1.76 μm quantum dash laser 60% of J_{th} is due to Auger recombination.

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1 Introduction

The deposition of InAs within AlGaInAs layers grown on conventional InP substrates can produce self-assembled, finite-length, quantum wire-like InAs structures (quantum dashes) with emission wavelengths 1.5 μm and longer. This makes these structures promising for near- and mid-infrared applications. Controlling the density of states in the active region of a semiconductor laser using quantum confinement makes it possible to restrict the injected electrons and holes to those levels where they can take part most efficiently in the stimulated emission process. This has been used effectively in quantum well lasers (2D) for many years and more recently self-assembled quantum dot (0D) structures have started to show promising characteristics [1]. Until very recently relatively little success has been achieved with quantum wire (1D) structures, though the first InAs quantum dash based lasers showed a number of promising characteristics like a broad gain spectrum [2, 3], small temperature dependence of the lasing wavelength (0.09–0.12 nm/K) [4, 5], anisotropic dependence of gain on orientation of the quantum dashes [2], room temperature threshold current density, J_{th} , of 0.4–2 kA/cm^2 (the lowest value of $J_{\text{th}} = 11.4 \text{ A}/\text{cm}^2$ was measured in 1.9 μm device at $T = 77$ K) [4, 6, 7], and a characteristic temperature, T_0 , of 60–84 K [4, 5] (where $T_0 = (d \ln J_{\text{th}}/dT)^{-1}$). In this paper we present what we believe to be the first ever high pressure measurements on quantum dash lasers, which we used to study the recombination and loss mechanisms giving rise to the relatively high threshold current density and thermal sensitivity of these lasers.

^{*} Corresponding author: e-mail: i.marko@surrey.ac.uk, Phone: +44 1483 68 94 09, Fax: +44 1483 68 94 04

2 Experiment

InAs quantum dashes were grown within electron and photon confinement structures on InP substrates. We studied two types of lasers. The active region of type-A devices, which emitted at 1.52 μm at room temperature, consisted of 4 InAs (5MLs) quantum dash layers embedded in an InGaAlAs/InP GRINSCH structure [4]. The active region of type-B devices was formed by 4 InAs (7.5 MLs) quantum dash layers placed in an InGaAlAs waveguide and it operated at 1.76 μm at room temperature. The lasers were as-cleaved broad area devices with 50- μm stripe contact and cavity lengths between 0.8–1.3 mm.

The lasers of A-type were characterized using measurements of un-amplified spontaneous emission from a window milled in the n-type contact [8]. This method allows for a study of the temperature dependence of the radiative component, J_{rad} , of total threshold current density, which is proportional to the integrated spontaneous emission at lasing threshold. The hydrostatic pressure dependence of the lasing wavelength and threshold current of both laser types were measured using piston in a cylinder pressure system [8] at room temperature. Using a He-gas pressure system similar measurements were carried out both at room temperature and at a low temperature of about 125 K. Applying high pressure allows the energy E_{las} of the emitted photons to be varied while keeping the basic properties of the band structure relatively unchanged. Various recombination mechanisms depend on E_{las} in different ways. For example, the radiative recombination contribution to the laser threshold current usually increases with pressure as E_{las}^2 in quantum well lasers, while the Auger recombination coefficient decreases [8]. In conjunction with other techniques, these variations allow one to determine the relative importance of these recombination mechanisms.

3 Results and discussion

We studied the threshold current, stimulated emission from the facet and unamplified spontaneous emission from a window as a function of temperature in the interval $T = 70\text{--}300\text{ K}$. As shown in Fig. 1, for both laser types the threshold current density, J_{th} , was about 2 kA/cm^2 at room temperature and had a similar temperature sensitivity, characterised by a T_0 of about 80 K in the range $T = 120\text{--}250\text{ K}$, and $T_0 = 59\text{ K}$ (1.52 μm device) and $T_0 = 67\text{ K}$ (1.76 μm device) in the temperature interval $T = 250\text{--}300\text{ K}$. Measurements of the spontaneous emission showed that the radiative part, J_{rad} , of the threshold current is less than 5% in the A-type devices at room temperature (this upper limit was measured assuming that at low temperature, $T = 70\text{ K}$, the total J_{th} is mainly due to radiative recombination), though the internal differential efficiency of these lasers was as high as 50%. Also J_{rad} is almost temperature independent as was observed previously in quantum dot lasers [8]. Therefore the relatively large value of J_{th} and its temperature sensitivity must be due to non-radiative recombination processes.

Fig. 1 Temperature dependence of the threshold current density, J_{th} , of the 1.52 μm (A-device) and 1.76 μm (B-device) quantum dash lasers. The radiative current for the A-device was determined from the integrated spontaneous emission at laser threshold.

Fig. 2 Laser emission photon energy, E_{las} , of the 1.52 μm laser at $T = 295$ K and of the 1.76 μm laser at $T = 135$ K and $T = 295$ K as a function of hydrostatic pressure.

Applying hydrostatic pressure, p , increased the band gap and lasing photon energy, E_{las} , towards higher energies as shown in Fig. 2. Both laser types showed a similar gradient dE_{las}/dp of about 80 meV/GPa, which was temperature independent. This indicates that the pressure variation of the band gap is the same in both structures at low ($T = 135$ K) and high ($T = 295$ K) temperatures. Therefore the different pressure dependencies of the threshold current in the structures with different emission wavelengths could be explained only by different dominant recombination processes.

The pressure dependence of the threshold current of the 1.52 μm quantum dash lasers (normalised at atmospheric pressure) measured at 125 K and 295 K, is shown in Fig. 3. The threshold current of these lasers was almost pressure independent both at low and high temperature. A small decrease of the threshold current of about 5% was observed at 1000 MPa at room temperature. Therefore at high temperature the dominant non-radiative recombination process, which causes the strong increase of the threshold current with increasing temperature, is pressure independent. From the previous analysis of the pressure dependence of different recombination processes in InAs quantum dot lasers [8] the radiative part, I_{rad} , of the threshold current increases with pressure as E_{las}^l , where $l > 1$. Only defect related current in the localised states and/or wetting layer, I_{defect} , is pressure independent, because hydrostatic pressure does not significantly change the band offsets of the structures. Auger recombination decreases strongly with increasing band gap and causes a decrease of threshold current at increasing pressure [8]. Therefore we believe that in the A-type devices, defect related recombination is the dominant process. This may be explained by the lower confinement energy in the shorter wavelength lasers, which allows temperature dependent thermal escape of carriers from the dashes followed by defect related recombination in the wetting layer or in the surrounding material. Assuming that the total threshold current consists mainly of

Fig. 3 Normalised threshold current $I_{\text{th}}(p)/I_{\text{th}}(0)$ of the 1.52- μm quantum dash lasers versus pressure at low ($T = 125$ K) and high ($T = 295$ K) temperature. The dashed line represents the calculated dependence using equation (1) and assuming that $I_{\text{rad}} = 5\%$, $I_{\text{mon}} = 80\%$, and $I_{\text{Aug}} = 15\%$ of I_{th} .

Fig. 4 Normalised threshold current $I_{th}(p)/I_{th}(0)$ for the 1.76- μm quantum dash lasers versus pressure at low ($T = 135\text{ K}$) and high ($T = 295\text{ K}$) temperature. The dashed line represents a fit to the experimental points at $T = 295\text{ K}$ using Eq. (1).

the radiative current, defect related current, Auger recombination current, I_{Aug} , as a first approximation we used the following expression to fit the measured pressure dependence [8]:

$$I_{th} = I_{rad} + I_{Aug} + I_{defect}, \quad \text{where} \quad I_{rad}(p) \sim E_g^2, \quad I_{Aug}(p) \sim E_g^{-1/2}, \quad I_{defect}(p) = \text{const.} \quad (1)$$

Judging from pressure independence of I_{th} at room temperature and using Eq. (1) we found that about 80% of I_{th} is due to defect-related current whilst Auger recombination accounts for 15% of I_{th} . Here we have assumed that the radiative current accounts for a maximum of 5% of I_{th} at atmospheric pressure (from the spontaneous emission measurements) and used the defect related current as a fitting parameter. The fact that the pressure results at low and high temperature are very similar shows that Auger recombination in the 1.52 μm quantum dash lasers is not the main recombination mechanism at high temperature as was observed earlier in 1.3 μm quantum dot lasers [8], though its influence may be larger if defect related recombination can be reduced. For the detailed quantitative analysis more investigations are needed. It was shown that in similar quantum dash lasers the external differential efficiency was almost constant with temperature over the range $T = 20\text{--}70\text{ }^\circ\text{C}$ [9]. Therefore in our analysis we assumed that the pressure variation of the optical losses due to intervalence band absorption and their influence on the threshold current are negligible.

Despite the similar temperature dependence of the threshold current in 1.52 μm and 1.76 μm quantum dash lasers, I_{th} decreased much faster with increasing pressure in the longer wavelength devices. The pressure dependence of I_{th} in the 1.76 μm lasers at $T = 135\text{ K}$ and $T = 295\text{ K}$ is presented in Fig. 4. The decrease of I_{th} was about 25% at 1000 MPa and at room temperature demonstrating that the main recombination path decreases strongly with increasing band gap. A small increase of threshold current at low temperature indicates the absence of this recombination process at low temperature. This is evidence of significant Auger recombination at higher temperature in the 1.76 μm quantum dash lasers. Assuming that Auger recombination is present and using Eq. (1), we estimated that Auger recombination causes loss of about 60% of the threshold current at room temperature. Though we have two degrees of freedom in Eq. (1), I_{rad} and I_{defect} , the fit of experimental points is possible only with I_{Aug} of about 60%. Variation of the ratio between the radiative and the defect related current does not change this number significantly.

This shows that in the longer wavelength 1.76 μm quantum dash lasers Auger recombination is much stronger than in the 1.52 μm devices and is the main reason for the thermal sensitivity of these lasers. Thus, decreasing the band gap and increasing the wavelength gives better carrier confinement and reduces defect related recombination in the 1.76 μm lasers, but it increases Auger recombination. These two effects almost compensate each other and lead to a very similar temperature dependence of threshold current density in the different quantum dash lasers.

4 Conclusion

We present what we believe to be the first ever high pressure measurements on quantum dash lasers where the active region consists of self assembled, finite length quantum wires. The characteristics of InAs/InP quantum dash lasers with emission wavelengths of 1.52 μm and 1.76 μm were studied as function of temperature and high hydrostatic pressure. The dramatically different pressure behaviours of the threshold current in these lasers can be interpreted assuming that in the 1.52 μm lasers, pressure independent defect related recombination outside the dashes due to thermal carrier spill-over dominates, while in the 1.76 μm quantum dash laser about 60% of I_{th} is due to Auger recombination. Our experimental results show that decreasing the band gap of quantum dashes and increasing the lasing wavelength improves carrier confinement and decreases defect related recombination. However this causes stronger Auger recombination in the longer wavelength devices. The results clearly illustrate the important role that high-pressure measurements play in understanding semiconductor optoelectronic devices.

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