Laser devices with stacked layers of InGaAs/GaAs quantum rings

Ferran Suárez, Daniel Granados, María Luisa Dotor and Jorge M García

Instituto de Microelectrónica de Madrid, CNM (CSIC), C/Isaac Newton 8, PTM, 28760-Tres Cantos (Madrid), Spain

E-mail: ferran@imm.cnm.csic.es

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Abstract

Stacked layers of In(Ga)As on GaAs(001) self-assembled quantum rings (QR) for laser application have been studied. Several samples with three stacked QR layers have been grown by molecular beam epitaxy with GaAs spacers from 1.5 to 14 nm. The optical and structural properties have been characterized by photoluminescence spectroscopy and by atomic force microscopy, respectively. For GaAs spacers larger than 6 nm, the stacked QR layers present similar properties to single QR layers. A semiconductor laser structure with three stacked layers of QR separated 10 nm in the active region has been grown. This spacer ensures well-developed rings with optical emission like that of a single layer. Laser diodes have been processed with 1–2 mm cavity lengths. The stimulated emission is multimodal, centred at 930 nm (77 K), with a threshold current density per QR layer of 69 A cm^{-2} . In this work, it is demonstrated that stacking rings is possible, and that a broad area laser with three QR layers can be fabricated successfully.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

During last few years, many efforts have been devoted to the fabrication of optoelectronic devices based on low dimensional semiconductor nanostructures. Significant improvements of the laser performance for optical communication systems have already been demonstrated, such as: low threshold current [1–3], temperature-insensitive operation [4, 5], large modulation bandwidth, low chirp and linewidth enhancement factor [6]. Self-assembled semiconductor quantum dots (QD), formed via lattice-mismatched heteroepitaxy (for example InAs/GaAs, InAs/InP, GaSb/GaAs), are currently being used for developing optoelectronic technologies and devices. A precise control over the QD height, width and shape is of crucial importance since these structural properties have a clear influence on the quantum confinement of the charge carriers and therefore determine their optoelectronic properties. Unfortunately, self-assembled dots do not have the flexibility of band gap engineering that quantum wells have. Commonly the size of the dots is critically determined by the optimal growing

conditions employed to obtain narrow size distributions. In the particular case of InAs on GaAs(001) QD, on which this work is focused, employing a different substrate temperature or changing the III/V element ratio may produce variations in the sizes of the dots, but also broadens the size distribution. This is one of the major problems if we aim to employ ensembles of these nanostructures in useful devices. A possible strategy for overcoming this problem consists in growing the QD under optimal conditions and modifying its vertical size during capping, without changing the embedding layers. A technique which is specially useful for reducing the vertical size, i.e. for obtaining shorter wavelengths [7], consists in partially covering the InAs islands with a thin cap of GaAs and letting the original islands ‘melt’ and re-shape. This process can be used to reduce the original vertical size of the QD in a controlled way with atomic height accuracy using, for example, the molecular beam epitaxy (MBE) growing technique. In particular, under specific growth conditions [8, 9] it is possible to obtain from each QD a self-assembled ‘nanovolcano’, or quantum ring (QR) [10, 11]. Unlike mesoscopic lithography-defined rings,

these QR, once embedded in a GaAs matrix, function in the true quantum limit, free of decoherence problems due to scattering processes [10]. The possibility of tailoring the potential confinement in each layer of dots is also of great significance if we aim to achieve a more flexible band gap engineering of 3D nanostructures [7, 12].

When QD are employed in the active region of laser devices, the use of stacked layers is necessary to avoid saturation gain effects. It has been shown [13] that the optical mode loss does not increase as the number of layers increase, whereas the modal gain obtainable from the dot ground state increases. When QR are employed in the active region, stacking the nanostructures is even more important due to the commonly low density of ring ensembles ($2\text{--}9 \times 10^9 \text{ cm}^{-3}$). The use of higher QR sheet densities could lead to overlap problems because of the large in-plane dimension of the rings ($100 \text{ nm} \times 90 \text{ nm}$). Although stacking of rings is of interest in much applied and fundamental research, it is not a solved problem. A lot of experimental and theoretical work has been reported on single layers of rings, but, as far as we know, only one theoretical work [14] on stacked QR, predicting parity coupling effects, has been published. Vertical coupling between QD may also allow their use for information processing. For high power laser devices, the low density of rings could be a drawback, but for applications such as Q-bit implementation, employing these nanostructures could be especially appropriate.

In this work, it is demonstrated that stacking rings is possible, and that a broad area laser with three QR layers can be fabricated successfully. The paper is organized as follows. After the description of the experimental set-up, the sample growth, the layout of the laser epitaxy and the device processing technology (section 2), an optical and structural characterization of various samples with three stacked layers of QR will be shown in section 3. The results from this section allow us to choose the optimum GaAs spacer between rings to use in the active region of the laser. Section 4 is focused on discussion of the characterization at different temperatures of the laser device processed with various cavity lengths.

2. Experimental set-up and sample growth

All the samples have been grown and the laser epitaxy carried out in a home-made solid source MBE. Group III cells, an As-valved cell with a cracker, the sample transfer, the sample oven and the shutter operation have been designed and built at the Institute of Microelectronics of Madrid. Reflection high energy electron diffraction (RHEED) has been used to monitor the onset growth of the QD and to calibrate both temperatures and growth rates.

The emission characteristics have been measured by photoluminescence spectroscopy (PL) with a 514.5 nm Ar laser line and a 0.22 m monochromator with a liquid nitrogen cooled Ge diode. The surface sample morphology has been characterized by contact mode atomic force microscopy (AFM).

Two sets of samples have been grown with three layers of QR, each sample with a different GaAs spacer between layers: 1.5, 3, 4.5, 6, 10 and 14 nm (see the inset of figure 1). In each layer, the total amount of deposited InAs was just above the critical thickness (Θ_c) necessary for the 3D transition

Figure 1. Critical thicknesses at which the QD nucleate in the first (square), second (triangles pointing up) or third (triangles pointing to the right) layer versus the GaAs spacer thickness. Inset: the scheme of a PL sample with three stacked layers of rings.

to take place (checked with RHEED). Commonly, Θ_c is ~ 1.6 ML for a single QD layer. Conversely, for 1.5 and 3 nm GaAs spacers, the nucleation of the second and the third layers takes place for coverage, Θ_c , significantly below 1.6 ML. This effect is probably due to strong In segregation and the strain propagation effect, as occurs with stacked QD for thicker spacers; whereas for a spacer 4.5 nm thick, or thicker, the nucleation of the second and third dots takes place for 1.6 ML, as in the first layer. Studies on cross section structural microscopy have been performed, confirming that the ring-shaped islands remain when these nanostructures are overgrown with GaAs or stacked in different layers. These results will be presented in further publications.

The AFM samples have the top layer of rings uncovered and are cooled down immediately after growth and removed from the chamber to be characterized *ex situ*. The PL set of samples has been obtained by capping similar structures with a thick GaAs layer.

The laser epitaxy has been performed under continuous rotation using As_4 for the whole structure, except for the ring layers where As_2 has been used. Separate confinement heterostructures (SCH) with Si and graded Be dopants have been used for the n^+ and p^+ cladding layers. The graded index waveguide (GRIN) has been grown with AlAs/GaAs short period superlattices. In the active region, three stacked layers of QR spaced by 10 nm of GaAs have been used. Full details of the layout for the laser epitaxy may be found in table 1.

Au–Ge–Au and Cr–Au have been used for the n and p contacts, respectively. Broad area lasers with $40 \mu\text{m}$ wide stripes with cleaved front and rear facets have been fabricated with cavity lengths (L) of 1, 1.5 and 2 mm. Diodes were mounted with the p side up onto copper heat sinks. Devices were tested under pulsed conditions (0.1% duty cycle) in a closed cycle temperature controlled helium cryostat. The spectra were analysed by a 0.22 m monochromator with an InGaAs photodetector.

3. Single and stacked layers of quantum rings

Figure 2(a) presents the AFM characterization of a self-assembled single layer of a typical InAs QD ensemble, grown under optimal conditions to obtain a narrow size distribution.

Table 1. QR laser structure.

Surface			
Cladding	50 nm	GaAs	Be doped = $1 \times 10^{19} \text{ cm}^{-3}$
	400 nm	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	Be doped = $5 \times 10^{18} \text{ cm}^{-3}$, $x = 0.60$
	640 nm	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	Be doped = $1 \times 10^{18} \text{ cm}^{-3}$, $x = 0.60$
	320 nm	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	Be doped = $8 \times 10^{17} \text{ cm}^{-3}$, $x = 0.60$
Waveguide	82 nm, $29 \times$	[5 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.50$	
	58 nm, $18 \times$	[7 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.42$	
	56 nm, $14 \times$	[9 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.36$	
	Active region	10 nm GaAs 2 ML InAs + 2 nm GaAs (growth pause and ring formation) 10 nm GaAs 2 ML InAs + 2 nm GaAs (growth pause and ring formation) 10 nm GaAs 2 ML InAs + 2 nm GaAs (growth pause and ring formation) 2.1 nm GaAs	
Cladding	56 nm, $14 \times$	[9 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.36$	
	58 nm, $18 \times$	[7 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.42$	
	82 nm, $29 \times$	[5 ML GaAs + 5 ML AlAs], equivalent to $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $x = 0.50$	
	1400 nm	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	Si doped = $1 \times 10^{18} \text{ cm}^{-3}$, $x = 0.60$

Figure 2. $1 \times 1 \mu\text{m}^2$ size AFM images of (a) a single layer of InAs/GaAs self-assembled QD, which are 11 nm high. When a growth pause is introduced during capping of QD with 2 nm, each island re-shapes into a QR (b). Meanwhile when three QR are stacked with GaAs spacers of 3 nm (c) there are a variety of ring-like structures with no well-defined shape; for a 6 nm spacer (d), the surface morphology is very similar to that of a non-stacked sample of QR.

The QR (figure 2(b)) were obtained after a growth interruption when the dots were partially covered with 2 nm of GaAs under an As_2 flux, letting the material rearrange [15].

The AFM images of stacked QR samples are presented in figure 2(c) (spacer of 3 nm) and figure 2(d) (spacer of 6 nm). Figure 2(c) clearly shows that for a 3 nm spacer there are at least two families of ring-like structures. The bigger rings have a large hole which is at least (probably limited by the AFM tip resolution) ~ 2.5 nm deep. Most probably, this hole is connecting a ring in the lower layer. The structure of these

large rings suggests that a large mass transfer has occurred from the buried layer of QR to the top layer.

The surface morphology of stacked layers of rings with a spacer of 6 nm (figure 1(d)) is very similar to the one observed for a single layer of rings. For the set of samples with larger GaAs spacers (not shown), the top QR layer has always presented the same aspect, suggesting that the rings should have similar properties to a single layer.

Figure 3(a) shows the PL spectra at 15 K of a sample with a single layer of QD and of a sample with a layer of QR, both buried with GaAs. It should be underlined that the only difference between the two samples is that a growth interruption has been introduced for the ring sample when the dots were capped with 2 nm of GaAs. The amounts of deposited InAs are the same in both samples. A large shift in the emission wavelength from 1135 nm (QD) to 915 nm (QR) is observed. This large blue-shift (~ 260 meV) is due to a vertical reduction of the effective confining potential and it clearly demonstrates at-will tuning of the wavelength emission of the dots.

The similarity of properties of single and stacked layers of rings with spacers larger than 6 nm, suggested by AFM analysis, has been confirmed by the optical properties analysis. The PL spectra at 15 K of three stacked layers of QR are presented in figure 3(b). For 1.5 and 3 nm spacers, the spectra are red-shifted with respect to the single-layer emission. This effect can be understood on the basis of a strong vertical electronic coupling between the nanostructures with column-like structures rather than isolated layers of rings. When a separation of 6 nm or more (not shown) was used between the layers of rings, the spectra were very similar to the one measured for a single layer.

These observations agree with the behaviour of the critical thickness required for QD formation (Θ_c) in each layer of the stacked rings (figure 1).

AFM characterization demonstrates that it is possible to grow stacked layers of QR using in each ring layer by the procedure described in [15]. For the fabrication with the laser, a 10 nm spacer between the layers of rings in the active region

Figure 3. Low temperature PL spectra of (a) QD and a QR ensemble. A strong blue-shift in wavelength is observed, from dot to ring emission. (b) PL emission from samples with three stacked layers of QR with 1.5, 3 and 6 nm GaAs spacers.

has been chosen. This spacer will ensure well-developed rings with optical emission like that of a single layer.

4. Laser characterization

Devices with cavity lengths (L) of 1, 1.5 and 2 mm have been tested under pulsed conditions. The light current characteristics for a $L = 1$ mm laser for a temperature range from 15 to 150 K are shown in figure 4. The minimum measured value of the threshold current density (J_{th}) is 69 A cm^{-2} per QR layer sheet at 77 K for a device with a cavity length $L = 2$ mm. No lasing emission is obtained above 150 K. It is observed that the threshold current becomes smaller with T decreasing from 150 to 77 K and, surprisingly, starts increasing below 77 K. Such effects occur for all cavity lengths studied, as can be seen in figure 4 inset, and can be explained taking into account that the short period superlattices of the waveguide are not totally transparent for low temperature [15]—below 77 K in this particular case. This is confirmed by the observation with the naked eye of an additional spontaneous emission in the red spectral region for the devices studied. These radiative recombination processes (and probably other non-radiative ones) are due to the presence of carriers in the optical confinement layer, giving rise to an additional component of the injection current resulting in $T_0 = -40$ K.

From 77 to 120 K, T_0 is 80 K, and for $T > 120$ K the T_0 value decreases to 40 K. The low values of T_0 may be explained by the small vertical carrier confinement of the QR, which are significantly shorter than the QD. Therefore, as the temperature is increased it is necessary to inject higher currents to maintain the threshold gain and compensate for the fraction of thermally evaporated carriers. At the same time, the volume of a QR active layer is one order (two orders) of magnitude smaller than

Figure 4. Light current characteristics of a 1 mm long QR laser at different temperatures. The inset shows the threshold current density versus T for 1, 1.5 and 2 mm cavity lengths.

a QD (quantum well) active layer. So their optical confinement (Γ) is also minor. The maximum expected gain (proportional to Γ) is low—becoming even lower as T increases—and this reduces the possibility of achieving a working laser device with three stacked layers of QR at room temperature. Even for a 2 mm cavity length, stimulated emission above 150 K has not been observed, suggesting gain saturation effects. The first way to overcome this limitation is to increase the active volume by stacking more than three layers of QR. Other approaches, used in order to obtain a temperature-insensitive QD laser, have been proposed based on band gap engineering. For example, the use of high confinement barriers next to the dots, in the active layer, will induce wide energy separations of electronic levels [16, 17]. Another method is based on selective tunnelling injection of carriers into the QD [18]. A novel approach recently published [19] is based on blocking the minority-carrier transport into the QD while leaving majority-carrier injection unimpeded.

Figure 5 shows the multimodal stimulated spectra from the cleaved edge measured at 120, 77, 50 and 15 K for $J_{th} = 1.6 J_{th}$. The laser emission clearly relates to recombination of carriers in the QR nanostructures, as can be deduced from its overlap with the QR PL broadband emission (see the inset of figure 5).

At 15 K there are measured two groups of multimode lines at 907 and 921 nm, separated by ~ 21 meV. The most intense mode emits at lower energy. The unexpected increment of the threshold current below 77 K with decreasing device temperature can be understood in terms of the loss of efficiency occurring because of the lack of transparency in the waveguide. Under high injection currents, the main mode operates together with the high energy lasing multimode.

5. Conclusions

In order to develop a QR laser device, stacked layers of QR have been studied for different GaAs spacers. We have seen proof that three stacked layers of QR are morphologically and optically similar to a single layer of QR for GaAs spacers thicker than 6 nm. For this reason, GRIN SCH laser epitaxy was carried out with a 10 nm GaAs spacer between QR in the active layer. Laser emission using three stacked layers of QR

Figure 5. Lasing spectra of a 1 mm cavity laser at 120, 77, 50 and 15 K. The inset shows the photoluminescence of three layers of QR (broad peak) and the laser emission (narrow peak) at 77 K.

in the active region was achieved for the first time, although working below 150 K. The absence of complete transparency of the waveguide below 77 K explains the observed negative $T_0 = -40$ K. The multimodal laser stimulated emission, centred at 930 nm at 77 K, clearly relates to the recombination of carriers in the QR as can be deduced from the observation of the stimulated emission within the QR PL broadband. The minimum threshold current density per QR layer is 69 A cm^{-2} at 77 K for a 2 mm cavity length. The traces of gain saturation above 150 K suggest that the active volume is not enough to achieve stimulated emission; therefore it is necessary to stack more than three sheets of QR in order to develop a laser device working at RT.

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