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High efficiency and high modal gain InAs/InGaAs/GaAs quantum dot lasers emitting at 1300 nm

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Abstract

High performance 1300 nm lasers based on self-organized InAs/InGaAs quantum dots (QDs) are reported. By optimizing the QD growth parameters and decreasing the waveguide thickness, a high modal gain and a low transparency current density of 32 cm^{-1} and 35 A cm^{-2} , respectively, were obtained from a device containing five stacked QD layers. The internal quantum efficiency is as high as 90%.

1. Introduction

Semiconductor quantum dots (QDs) are a promising way for the realization of high performance laser diodes. Theoretical predictions of the intrinsic properties of QD lasers, such as strongly increased gain and differential gain, are expected to provide ultra-low threshold current density, large modulation bandwidth and high characteristic temperature [1, 2]. The InAs/InGaAs/GaAs system has received a strong interest in the last few years. Room temperature continuous-wave operation lasers with high characteristic temperature, low threshold current density and high output power were reported [3–5]. However, in comparison with quantum well (QW) lasers, QD lasers still suffer from a low modal gain, which limits the modulation bandwidth and prevents the fabrication of short in-plane cavity devices. This limitation is due to both the low QD density and the small overlap of QD layers with the optical field. This problem is generally solved by stacking several QD layers and by carefully designing the laser structure, in particular the waveguide thickness. Moreover, the growth parameters should be optimized in order to preserve the same optical properties for each stacked layer.

In this work, we show that by growing highly uniform stack of QDs and by reducing the waveguide thickness, the modal gain can be increased up to 32 cm^{-1} from five InAs/InGaAs QD layers. This modal gain of 6.4 cm^{-1} per QD layer, normalized to the quantum dot density, is, to our knowledge, the highest value obtained from the five QD layer semiconductor laser. The enhancement of the modal gain is

accompanied by a decrease of the threshold and transparency current densities per QD layer down to 16 and 7 A cm^{-2} , respectively.

2. Experiment

The samples investigated in this study were grown by solid source molecular beam epitaxy (MBE) on 2 inch In-free mounted (1 0 0) GaAs substrates in a RIBER COMPACT 21-T system equipped with a valved As cracker cell. The grown structures are as follows: a 200 nm thick n-type GaAs buffer, a $1.5 \mu\text{m}$ thick $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ n-type ($5 \times 10^{17} \text{ cm}^{-3}$, Si) cladding layer, an undoped active zone consisting of five stacked InAs/In_{0.18}Ga_{0.82}As QD layers spaced by four 40 nm thick GaAs electronic barriers and enclosed by 205, 105 and 55 nm thick GaAs spacers (for structures A, B and C, respectively), a $1.5 \mu\text{m}$ thick p-type $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ ($2 \times 10^{18} \text{ cm}^{-3}$, Be) cladding layer and finally a 300 nm p⁺-GaAs cap layer. Each dot layer consists of 2.8 monolayers (ML) of InAs grown on GaAs and is capped by 4 nm In_{0.18}Ga_{0.82}As. The use of InGaAs quantum well on the top of the QD layers provides a more efficient carrier capture to the QDs states. The indium containing layers and the first 5 nm thick GaAs layer were grown at low temperature, whereas the remaining 35 nm of GaAs barrier was grown at high temperature to avoid defects formation. More details concerning the growth can be found in [6]. The QD density measured by AFM on an uncapped sample is $3.2 \times 10^{10} \text{ cm}^{-2}$ with size dispersion

Figure 1. Photoluminescence emission at room temperature from unprocessed samples containing five stacked QD layers with different total active region thicknesses (600, 400 and 300 nm for structures A, B and C, respectively). The ground state FWHM of all samples is 26 meV. The laser emission spectrum of a 1 mm cavity length device is also shown.

Figure 2. Reciprocal differential quantum efficiency of five QD layer laser devices as a function of the cavity length in the pulsed regime (0.2%, 2 μ s) and at room temperature for three structures with different total active region thicknesses (600, 400 and 300 nm for structures A, B and C, respectively).

around 7%. Both density and uniformity are preserved during stacking. Fabry–Perot lasers with 120 μ m wide metal contact stripes were fabricated from the grown wafer. The lasers with uncoated facets were tested at room temperature and in pulsed regime to avoid thermal effects.

3. Results and discussion

Figure 1 shows the photoluminescence (PL) emission from as-grown samples. The PL emission from the ground state is close to 1300 nm and the full width at half maximum (FWHM) of the ground state is 26 meV for all the samples, indicating good size uniformity of QDs. We note that the energy difference between the two transitions is quite large, ranging from 79 meV to 88 meV, due to the large size of the QDs and the low aspect ratio ($5/45 = 0.11$). The laser emission of a 1 mm cavity length device at room temperature is also shown in figure 1 and is centred at 1307 nm. Figure 2 shows the reciprocal differential quantum efficiency as a function of the cavity length for the three structures (structures A, B and C) with the total active region thicknesses of 600, 400 and 300 nm, respectively. Using a linear fitting, we have extracted the internal quantum efficiency η_i and the internal

Figure 3. Threshold current density as a function of the total loss (modal gain at threshold) at room temperature and in the pulsed regime (0.2%, 2 μ s) of three laser structures with different total active region thickness and having five QD layers in the active region. Dashed lines indicate the saturation modal gain.

loss α_i using the following relationship:

$$\frac{1}{\eta_d} = \frac{1}{\eta_i} \left(1 + \frac{\alpha_i}{\alpha_m} \right),$$

where η_d is the external quantum efficiency and α_m is the mirror loss given by $\frac{1}{L} \ln \left(\frac{1}{R} \right)$, L being the cavity length and R the reflectivity of the laser facets. The external differential efficiency (η_d) was estimated from the room temperature light–current characteristics measured on devices of different length. η_i is deduced for a cavity length equal to 0. The values of α_i and η_i for the three structures are summarized in table 1. η_i increases from 70% for structure A to 74% for structure B and it reaches a value as high as 90% for structure C. As expected, the internal quantum efficiency is improved in thinner waveguide structures, because the probability of carrier capture into the QDs is higher and the non-radiative recombination rate is lower. The broadening of the waveguide can lead to a drastic reduction in the internal quantum efficiency due to the increased carrier density in the optical confinement layer of the optical waveguide as demonstrated in [7].

On the other hand, the internal losses are ≈ 3 cm^{-1} , 9 cm^{-1} and 14 cm^{-1} for structures A, B and C, respectively. This result is mainly due to the enhancement of the free carrier absorption induced by the increased overlap of the evanescent field with the cladding layers, as the waveguide thickness is reduced. In fact, in our structures the cladding confinement factor increases from $\approx 12\%$ for the structure A to $\approx 25\%$ for structure B and $\approx 38\%$ for structure C. By knowing the values of the internal losses for both structures, we have calculated the total losses $\alpha_i + \alpha_m$. In figure 3 we have plotted the threshold current density as a function of the total losses. The data were fitted by the empirical relationship

$$J_{th} = J_{tr} + \frac{J_{tr}}{\gamma} \ln \left(\frac{g_{sat}}{g_{sat} - g_{mod}} \right),$$

in which J_{th} and J_{tr} are the threshold and transparency current densities, respectively, γ is a fitting parameter, g_{sat} is the saturation modal gain and g_{mod} is the modal gain [8]. g_{mod} is related to the material gain G_m by the relationship $g_{mod} = \Gamma_{QD} \times G_m$.

The saturation modal gain increases from 22 cm^{-1} (structure A) to 30 cm^{-1} (structure B) and 32 cm^{-1} (structure C). The increasing value of the modal gain can be explained

Table 1. Internal losses, cladding confinement factor, internal quantum efficiency, QD confinement factor and the modal gain for the three QD laser structures.

Structure	Total active region thickness (nm)	Internal losses, α_i (cm ⁻¹)	Cladding confinement factor (%)	Internal quantum efficiency, η_i (%)	QDs confinement factor, Γ_{QD} (%)	Modal gain, g_m (cm ⁻¹)
A	600	3	12	70	0.76	22
B	400	9	25	74	0.87	30
C	300	14	38	90	0.89	32

mainly by the increasing value of the QD optical confinement factor Γ_{QD} which is estimated to be 0.76, 0.87 and 0.89% for structures A, B and C, respectively, as indicated in table 1. The QD optical confinement calculation was performed by considering the QD layer as a QW with equivalent thickness of 2.8 ML, which are the deposited monolayers of InAs. It is obvious that the obtained value is relatively lower than that of a classical QW with a typical thickness of 8–10 nm. Fray *et al* have reported a QD confinement factor of 0.17% for a single quantum dot layer, which is in good agreement with our calculation (0.76–0.89% for five QD layers) [9].

As indicated previously, the modal gain increases with increasing internal losses. The highest modal gain per QD layer obtained from structure C is 6.4 cm⁻¹, which to the best of our knowledge is the highest value for a multi-stacked QD laser emitting at 1300 nm with a comparable QD density. This value normalized to the QD density is twice the value obtained from a comparable semiconductor laser structure (8.1 cm⁻¹) with a higher QD density of 8×10^{10} cm⁻² [10]. The high modal gain value validates the very good reproducibility of the optical properties and the good size uniformity of different QD layers in the stacked structure, and is also related to the relatively large energy difference between the ground and excited states. A modal gain per QD layer of 2.4 and 3.5 cm⁻¹ was previously reported from laser structures containing ten QD layers [11,12]. The increased modal gain is accompanied by the reduction of the threshold and transparency current density. The transparency current densities per QD layer are 17, 9 and 7 A cm⁻² and the threshold current densities for an infinite cavity length per QD layer are 19, 17 and 16 A cm⁻².

The optimization of the growth parameters, to obtain a good size uniformity of the QDs with a large size and a high aspect ratio, and the use of a relatively large thick GaAs barriers allow the stacking of several QD layers in the same active region, preserving the same optical properties for the second and the subsequent layers. In addition, a reduction of the waveguide thickness is necessary in order to increase QD optical confinement and to consequently obtain a high modal gain. Structure C seems to give the best results in terms of modal gain and internal quantum efficiency. However, a higher internal loss value limits the external quantum efficiency for this sample. To decrease the internal losses by keeping a high value of the modal gain, a graded index separate confinement heterostructure (GRINSCHE) could be used.

4. Conclusion

In conclusion, we demonstrated high performance laser devices containing five stacked QD layers. A modal gain of 32 cm⁻¹ has been achieved at room temperature and at 1307 nm; the transparency current density per QD layer was

as low as 7 A cm⁻². Internal quantum efficiency as high as 90% is obtained.

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References

- [1] Asada M, Miyamoto Y and Suematsu Y 1986 Gain and the threshold of three dimensional quantum-box lasers *IEEE J. Quantum Electron.* **22** 1915–21
- [2] Arakawa Y and Sakaki H 1982 Multidimensional quantum well laser and temperature dependence of its threshold current *Appl. Phys. Lett.* **40** 939–41
- [3] Mikhlin S S *et al* 2005 High power temperature-insensitive 1.3 μ m InAs/InGaAs/GaAs quantum dot lasers *Semicond. Sci. Technol.* **20** 340–42
- [4] Liu H Y, Childs D T, Badcock T J, Groom K M, Sellers I R, Hopkinson M, Hogg R A, Robbins D J, Mowbray D J and Skolnick M S 2005 High-performance three-layer 1.3- μ m InAs–GaAs quantum-dot lasers with very low continuous-wave room-temperature threshold currents *IEEE Photonics Technol. Lett.* **17** 1139–41
- [5] Wilk A, Kovsh A R, Mikhlin S S, Chaix C, Novikov I I, Maximov M V, Shernyakov Yu M, Ustinov V M and Ledentsov N N 2005 High-power 1.3 μ m InAs/GaInAs/GaAs QD lasers grown in a multiwafer MBE production system *J. Cryst. Growth* **278** 335–41
- [6] Salhi A, Martiradonna L, Visimberga G, Tasco V, Fortunato L, Todaro M T, Cingolani R, Passaseo A and De Vittorio M 2006 High-modal gain 1300 nm In(Ga)As/GaAs quantum dot lasers *IEEE Photonics Technol. Lett.* **18** 1735–7
- [7] Ryvkin B S and Avrutin E A 2005 Effect of carrier loss through waveguide layer recombination on the internal quantum efficiency in large-optical-cavity laser diodes *J. Appl. Phys.* **97** 113106
- [8] Zhukov A E *et al* 1999 Gain characteristics of quantum dot injection lasers *Semicond. Sci. Technol.* **14** 118–23
- [9] Fry P W *et al* 2000 Modal gain and lasing states in InAs/GaAs self-organized quantum dot lasers *J. Appl. Phys.* **87** 615–7
- [10] Amano T, Sugaya T and Komori K 2006 1.3- μ m InAs quantum-dot laser with high dot density and high uniformity *IEEE Photonics Technol. Lett.* **18** 619–21
- [11] Zhukov A E *et al* 2003 High external differential efficiency and high optical gain of long-wavelength quantum dot diode laser *Physica E* **17** 589–92
- [12] Sugawara M, Hatori N, Ishida M, Ebe H, Arakawa Y, Akiyama T, Otsubo K, Yamamoto T and Nakata Y 2005 Recent progress in self-assembled quantum-dot optical devices for optical telecommunication: temperature-insensitive 10 Gb s⁻¹ directly modulated lasers and 40 Gb s⁻¹ signal-regenerative amplifiers *J. Phys. D: Appl. Phys.* **38** 2126–34