Semiconductors, 2022, Vol. 56, No. 12

Relationship between wavelength and gain in lasers based on quantum wells, dots, and well-dots

© *G.O. Kornyshov[1], N.Yu. Gordeev[2], Yu.M. Shernyakov[2], A.A. Beckman[2], A.S. Payusov[2], S.A. Mintairov[2], N.A. Kalyuzhnyy[2], M.V. Maximov[1]*

[1] Alferov Federal State Budgetary Institution of Higher Education and Science
Saint Petersburg National Research Academic University of the Russian Academy of Sciences,
194021 St. Petersburg, Russia
[2] Ioffe Institute,
194021 St. Petersburg, Russia
E-mail: supergrigoir@gmail.com

Received December 2, 2022
Revised December 7, 2022
Accepted December 7, 2022

A systematic study of a series of InGaAs/GaAs lasers in the $1-1.3\,\mu$m optical range based on quantum wells (2D), quantum dots (0D), and quantum well-dots of transitional (0D/2D) dimensionality is presented. In a wide range of pump currents, the dependences of the lasing wavelength on the layer gain constant, a parameter which allows comparing lasers with different types of active region and various waveguide designs, are measured and analyzed. It is shown that the maximum optical gain of the quantum well-dots is significantly higher, and the range of lasing rawavelengths achievable in edge-emitting lasers without external resonators is wider than in lasers based on quantum wells and quantum dots.

Keywords: semiconductor laser, quantum well, quantum dots, quantum well-dots, optical gain.

DOI: 10.21883/SC.2022.12.55151.4408

1. Introduction

Most modern InGaAs/GaAs semiconductor devices (specifically, lasers, amplifiers, photodiodes, and solar cells) have active regions based on quantum wells (QWs) and quantum dots (QDs). QWs are used widely due to their high optical gain, which may reach $48\,\mathrm{cm}^{-1}$ for a single QW layer [1]. At the same time, elastic stresses in quantum wells impose technological constraints on their thickness and number. This makes the epitaxial growth technology considerably more complicated and suppresses the optical gain of devices with operating wavelengths $> 1\,\mu$m. Quantum dots are free from these problems, since active region layers are not subjected to elastic stress. However, owing to the low density and size dispersion of QDs, the characteristic optical gain value is $\leq 5-8\,\mathrm{cm}^{-1}$ [2]. QD lasers operate in a wide wavelength range, but may switch to lasing through an excited state at higher pump currents due to saturation of the ground-state gain.

A number of research groups are currently working on the fabrication of hybrid heterostructures combining the advantages of QWs and QDs. We have proposed and tested a new type of InGaAs/GaAs nanostructures that are characterized by a transitional (0D/2D) dimensionality and were called quantum well-dots (QWDs) [3,4]. A QWD is an ultradense uniform array of regions with a high In concentration inside a quantum well with a low In concentration. It was demonstrated that QWDs are similar to quantum dots in that up to 20 QWD layers [5] may be grown in an active region without dislocations due to a drop in elastic stresses. This stress relaxation also allows one to expand a waveguide, thus providing the needed modal gain for high-power lasers [6]. An optical gain of $33\,\mathrm{cm}^{-1}$ in a single QWD layer, which is much higher than the corresponding value for QDs and comparable to the one for QWs, was demonstrated experimentally [7]. Quantum well-dots were proven to be efficient in high-power edge-emitting lasers [8], solar cells, and microdisc lasers [9].

Data on spectral features of radiation of the active region are crucial for the design of diode lasers with the needed parameters. The lasing wavelength (an important parameter of a semiconductor laser) is specified by the optical characteristics of the waveguide and the cavity and the dependence of the gain spectrum on the pump current. An analytical expression for the dependence of optical gain of quantum wells on the pump current was derived in [10], and the corresponding empirical expressions for quantum dots and QWDs were proposed in [2] and [11], respectively. The number of layers in the active region and the gain of a single layer affect the modal gain and, consequently, the emission wavelength. In the present study, we examine systematically the dependence of the lasing wavelength on the optical gain for a series of InGaAs/GaAs laser structures of the optical range $(1-1.3\,\mu\mathrm{m})$ with different waveguide designs based on QWs, QDs, and QWDs.

2. Method of comparison of laser structures of different types

It is rather hard to compare the gain of laser structures with different types of an active region and different designs of an optical waveguide. The modal gain depends both on the number of active layers and on the waveguide thickness and the position of the active region in it. The material gain also cannot be regarded as a universal parameter, since it is very hard to determine it for quantum dots and quantum well-dots. The concept of material gain has no physical meaning for these objects.

We have recently proposed to use layer gain constant γ, which is a composition of thickness d of an active layer and its material gain G [12], as an approach to such problems:

$$\gamma = d \cdot G. \tag{1}$$

The physical meaning of this parameter is as follows: $\exp(\gamma)$ is equal to the gain coefficient of light that propagated without reflections normally through a layer with thickness d and material gain G. Since the layer thickness remains unchanged, the layer gain constant depends on the current in the same way as the material gain does. In the general case, the values of d and G are not known, but their product is fairly easy to determine, since the material gain is related to modal gain g:

$$G = g/\Gamma, \tag{2}$$

where Γ is the optical confinement factor of the active layer. It follows from (1) and (2) that

$$\gamma = g \cdot d/\Gamma. \tag{3}$$

d/Γ is known as the equivalent spot size or effective mode width. Since the optical mode intensity remains almost unchanged within the quantum-dimensional active layer, the equivalent thickness may be calculated, without any loss in accuracy, for a certain virtual layer with thickness d', which is positioned in the same way as the active layer, instead of the actual active layer itself with thickness d, which is often not known. Thus,

$$d/\Gamma = d'/\Gamma', \tag{4}$$

where Γ' is the optical confinement factor of the virtual layer. Taking this into account, we obtain

$$\gamma = g \cdot d'/\Gamma'. \tag{5}$$

The modal gain is a measurable parameter [11] in expression (5), while the effective mode width is a calculated one. Note that it is convenient to use a modal gain value normalized to the number of active layers.

3. Experiment

Laser structures for studies were grown on an n^+ GaAs substrate. Molecular beam epitaxy was used for QD structures, while QW and QWD structures were synthesized by metalorganic vapor-phase epitaxy. The QWD samples were distinct in that the active regions of structures of the same spectral range were uniform in composition, thickness of the active layer, and growth process parameters. Lasers were designed as separate-confinement double heterostructure with an InGaAs active region in a GaAs waveguide with *p*- and *n*-type AlGaAs emitters. A total of 37 structures, which differed in dimensionality and the number of nanostructure layers in the active region, its positioning within the waveguide, the waveguide thickness, the Al concentration in emitters, and the emission wavelength (see the table), were examined. Effective mode width d'/Γ' was calcu;ated for each structure.

Stripe lasers with a stripe width of $100\,\mu$m were fabricated from the grown structures by standard photolithography processing. Dielectric mirrors were not deposited on cleaved faces of lasers. Lasers $250-4000\,\mu$m in length were mounted on copper heatsinks with the *p*-side facing down, and the threshold current density, the emission wavelength, and the differential quantum efficiency were measured for them under pulsed pumping. The values of internal optical loss α_{in} and the internal quantum efficiency of stimulated emission [10] for each structure were derived from the obtained dependences of reciprocal differential quantum efficiency on the laser cavity length. Modal gain $g = \alpha_{\text{in}} + \alpha_{\text{out}}$ was determined as the sum of internal (α_{in}) and external (α_{out}) optical losses for each laser from the sample. Multiplying g, which was normalized to the number of active layers, by calculated d'/Γ', we find the value of γ per a single active region layer. Since the material gain is measured in reciprocal centimeters, the obtained gain constant is a dimensionless quantity.

4. Results and discussion

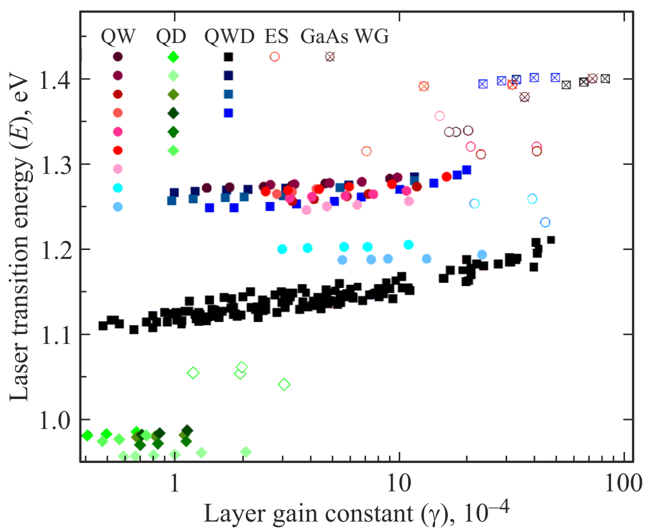
The maximum measured γ values are close in magnitude to the ones derived from experimental waveguide absorption data [12]. Dependences of the optical photon energy on gain constant γ were plotted for all the studied laser structures (see the figure). QW lasers reach a gain constant close to $20-30 \cdot 10^{-4}$ and then switch to lasing through an excited state. The lasing wavelength of QD structures switches abruptly (50 meV, 100 nm) from the ground state to an excited one at significantly lower values of the gain constant $(\sim 2 \cdot 10^{-4})$. The highest layer gain constant $(47 \cdot 10^{-4})$ was measured in the structure with a single QWD layer. The plot demonstrates that QWDs differ fundamentally from QWs and QDs: they lack lasing through an excited state. At the maximum gain constant values, lasing of the GaAs waveguide states at 1.4 eV (at a wavelength of 880−890 nm) emerges in them, just as in all the other heterostructures. QWDs emitting at 980 and 1060 nm behave in a similar way.

The rate of variation of photon energy (E) with γ is the highest in structures with QDs, where $dE/d\gamma \sim 120\,\text{eV}/\gamma$. The variation for QWs is $17\,\text{eV}/\gamma$. However, the range of variation of constant gain in QDs is an order of magnitude narrower than in the other structures; therefore, only a minor shift of the lasing wavelength is feasible. The rate of variation of the photon energy in QWD structures decreases with increasing gain constant from 45 to $20\,\text{eV}/\gamma$.

Types of laser structures studied

Active region type	Number of active region layers	Emission wavelength of a long chip, μm	Maximum layer gain constant, $\times 10^{-4}$	Structure design reference
QWD	1	1.08	47	[13]
	2	1.09	40.8	[14]
	2	0.98	19.8	[6]
	4	1.1	9.3	[15]
	5	1.1	19.8	[14]
	6	1.1	6.8	[15]
	8	1.1	4.3	[4]
	10	1.1	4.5	[3]
QW	1	0.98	10.9	[13]
	2	0.98	16.1	[16]
	2	1.04	23.1	[17]
QD	5	1.28	2.1	[13]
	10	1.28	1.2	[18]

The most striking feature of the QWD active region is that the gain constant may change by 2 orders of magnitude within the $0.45-47 \cdot 10^{-4}$ range and the overall range of variation of the laser photon energy is 110 meV (> 90 nm). These data agree well with the width of the gain spectrum for a laser with a single QWD layer determined using the Hakki–Paoli method [7]. This provides an intriguing opportunity to fabricate lasers with significantly different emission parameters (wavelength, threshold current, etc.) using one and the same growth technology for the active region. The simplest case is a laser with a large number of active QWD layers: owing to a higher γ-factor, it will have lower values of the gain constant and, consequently, the laser photon energy (a longer lasing wavelength).



Dependence of the laser transition energy on layer gain constant γ for QW, QD, and QWD laser structures. Lasing through an excited state (ES) and GaAs waveguide lasing (GaAs WG) are represented by open symbols and open crossed symbols, respectively.

5. Conclusion

The layer gain constant, which is a recently proposed measurable parameter, was used to compare different active regions within waveguides of different types. It was demonstrated that lasing is achieved within a wide range of layer gain constant values in InGaAs lasers based on quantum well-dots. The laser photon energy varies in this range by 110 meV, which exceeds considerably the corresponding values for InGaAs active media with quantum wells and quantum dots. Thus, any needed lasing wavelength within this wide optical range may be set in edge-emitting QWD lasers without the use of an external optical resonator. Combined with wide gain spectra, these features of quantum well-dots make them a promising active medium for various optoelectronic devices (specifically, edge-emitting lasers, amplifiers, and superluminescent diodes).

Funding

This work was supported by the Russian Science Foundation (project No. 22-22-00557), https://rscf.ru/project/22-22-00557/

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.P. Ongstad, G.C. Dente, M.L. Tilton, J. Stohs, D.J. Gallant. Appl Phys Lett., **72**, 836 (1998).

[2] A.E. Zhukov, A.R. Kovsh, V.M. Ustinov, A.Y. Egorov, N.N. Ledentsov, A.F. Tsatsul'nikov, M.V. Maximov, Y.M. Shernyakov, V.I. Kopchatov, A.V. Lunev, P.S. Kop'ev, D. Bimberg, Z.I. Alferov. Semicond. Sci. Technol., **14**, 118 (1999).

[3] S.A. Mintairov, N.A. Kalyuzhnyy, V.M. Lantratov, M.V. Maximov, A.M. Nadtochiy, S. Rouvimov, A.E. Zhukov. Nanotechnology, **26**, 385202 (2015).

[4] A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhnyy, Yu.M. Shernyakov, G.O. Kornyshov, A.A. Serin, A.S. Payusov, V.N. NevedomskyN.Yu. Gordeev, M.V. Maximov, A.E. Zhukov. Tech. Phys. Lett., **45**, 163 (2019)

[5] S.A. Mintairov, N.A. Kalyuzhnyy, M.V. Maximov, A.M. Nadtochiy, S. Rouvimov, A.E. Zhukov. Electron Lett., **51**, 1602 (2015).

[6] G.O. Kornyshov, A.S. Payusov, N.Y. Gordeev, A.A. Serin, Y.M. Shernyakov, S.A. Mintairov, N.A. Kalyuzhnyy, A.M. Nadtochiy, M.V. Maximov, A.E. Zhukov. J. Phys. Conf. Ser., **1400**, 6 (2019).

[7] G.O. Kornyshov, N.Y. Gordeev, A.S. Payusov, A.A. Serin, Y.M. Shernyakov, S.A. Mintairov, N.A. Kalyuzhnyy, M.V. Maximov, A.E. Zhukov. J. Phys. Conf. Ser., **1697**, 1 (2020).

[8] M.V. Maximov, N.Yu. Gordeev, Yu.M. Shernyakov, A.S. Payusov, S.A. Mintairov, N.A. Kalyuzhnyy, G.O. Kornyshov, A.A. Serin, A.A. Usikova, I.M. Gadzhiev, M.M. Kulagina, A.M. Nadtochiy, A.E. Zhukov. Proc. SPIE, **11356**, 113560A (2020).

[9] E.I. Moiseev, N.V. Kryzhanovskaya, M.V. Maximov, F.I. Zubov, A.M. Nadtochiy, M.M. Kulagina, Yu.M. Zadiranov, N.A. Kalyuzhnyy, S.A. Mintairov, A.E. Zhukov. Optics Lett., **43**, 4554 (2018).

[10] L.A. Coldren, S.W. Corzine, M.L. Mashanovitch. Diode Lasers and Photonic Integrated Circuits (N.Y., USA, Wiley, 2012).

[11] N.Y. Gordeev, M.V. Maximov, A.S. Payusov, A.A. Serin, Y.M. Shernyakov, S.A. Mintairov, N.A. Kalyuzhnyy, A.M. Nadtochiy, A.E. Zhukov. Semicond. Sci. Technol., **36**, 015008 (2021).

[12] A.M. Nadtochiy, N.Y. Gordeev, A.A. Kharchenko, S.A. Mintairov, N.A. Kalyuzhnyy, Y.S. Berdnikov, Y.M. Shernyakov, M.V. Maximov, A.E. Zhukov. J. Lightwave Technology, **39**, 7479 (2021).

[13] A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhnyy, M.V. Maximov, D.A. Sannikov, T.F. Yagafarov, A.E. Zhukov. Semiconductors, **53**, 1489 (2019).

[14] A.S. Payusov, Y.M. Shernyakov, A.A. Serin, A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhnyy, M.M. Kulagina, A.E. Zhukov, N.Y. Gordeev, M.V. Maximov. J. Phys. Conf. Ser., **1135**, 1 (2018).

[15] A.S. Payusov, M.I. Mitrofanov, G.O. Kornyshov, A.A. Serin, G.V. Voznyuk, M.M. Kulagina, V.P. Evtikhiev, N.Yu. Gordeev, M.V. Maksimov, S. Breuer. Tech. Phys. Lett., **48**, 87 (2022)

[16] A.A. Serin, A.S. Payusov, Y.M. Shernyakov, N.A. Kalyuzhnyy, S.A. Mintairov, N.Y. Gordeev, F.I. Zubov, M.V. Maximov, A.E. Zhukov. J. Phys. Conf. Ser., **1124**, 4 (2018).

[17] N.Yu. Gordeev, A.S. Payusov, Y.M. Shernyakov, S.A. Mintairov, N.A. Kalyuzhnyy, M.M. Kulagina, M.V. Maximov. Optics Lett., **40**, 2150 (2015).

[18] A.S. Payusov, A.A. Serin, G.O. Kornyshov, M.M. Kulagina, M.I. Mitrofanov, G.V. Voznyuk, V.P. Evtikhiev, M.V. Maximov, N.Y. Gordeev. Semiconductors, **54**, 1811 (2020).