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Semiconductor quantum dots devices: Recent advances and application prospects

J. P. Reithmaier[*, 1, 2], **A. Somers**[1], **W. Kaiser**[1], **S. Deubert**[1], **F. Gerschütz**[1], **A. Forchel**[1], **O. Parillaud**[3], **M. Krakowski**[3], **R. Alizon**[4], **D. Hadass**[4], **A. Bilenca**[4], **H. Dery**[4], **V. Mikhelashvili**[4], **G. Eisenstein**[4], **M. Gioannini**[5], **I. Montrosset**[5], **T. W. Berg**[6], **M. van der Poel**[6], **J. Mørk**[6], and **B. Tromborg**[6]

[1] Technische Physik, Physikalisches Institut, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
[2] Technische Physik, Institute of Nanostructure Technologies and Analytics, Universität Kassel, Heinrich-Plett-Str. 40, 34132 Kassel, Germany
[3] Alcatel-Thales III–V Lab, Route départementale 128, 91767 Palaiseau, France
[4] Electrical Engineering Dept. Technion, 32000 Haifa, Israel
[5] Dipartimento di Elettronica and PhotonLab, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[6] COM · DTU, NanoDTU, Technical University of Denmark, 2800 Lyngby, Denmark

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In this paper, a brief review will be given on recent advances in semiconductor quantum dots based optoelectronic devices. The focus will be on two major application areas, i.e., telecom devices and high power light sources, where some device examples will be discussed on the current status and for the future prospects.

1 Introduction

The reduction of the dimensionality of electronic systems in semiconductors allows to utilize basic quantum mechanical effects to control macroscopic material properties relevant to device applications. Quantum dots structures confine electrons in all three dimensions and allow in principle within a certain range a full control of the transition energies and the recombination location [1]. Due to the spectral and spatial localization of electrons one expect several advantages in comparison to conventional quantum well lasers, e.g., lower threshold current density [2] and temperature stabilized laser performance [3, 4]. Beyond these basic advantages, one can also tailor optical properties by directly controlling the dot geometry, e.g., dots density, size and size distribution. This allows, e.g., a nearly full internal temperature compensation of the transition energy in lasers [5] and to realize wavelength stabilized high power lasers without external cooling [6]. However, also other optoelectronic devices, like semiconductor optical amplifiers (SOAs) gain from basic properties of quantum dots structures, like local carrier storage, which allows very fast amplification responses for high speed transmission systems [7].

Recent results and future developments on those two areas of applications, i.e., quantum dots devices for high power and telecom applications, will be discussed in more details in this paper on the basis of a few examples.

* Corresponding author: e-mail: jpreith@physik.uni-kassel.de, Phone: +49 561 804 4430, Fax: +49 561 804 4136

2 High speed quantum dots devices for telecom applications

For telecom applications the 1.3 and 1.55 µm wavelength ranges are most important. While for 1.3 µm the widely investigated In(Ga)As/GaAs quantum dot material system can be used, the 1.55 µm wavelength range could be hardly reached. Only with pseudomorphic buffers one can partially compensate the large lattice mismatch to achieve 1.49 µm laser emission with reasonable threshold current densities [8]. To cover the whole long wavelength communication range between 1.4–1.65 µm, InP based structures are currently more suitable [9, 10].

2.1 InP based quantum dashes lasers

On [001] oriented InP substrates the formation of islands can be manifold dependent on the growth process and the surface material. An overview is given in [11]. We have used a process, which forms elongated dots (quantum dashes) with high areal density as can be seen in Fig. 1 in a cross section transmission microscope (XTEM) image [12].

The high density of dashes allows also short cavity lasers with quantum dot-like material due to the higher modal gain of these structures. The laser characteristics of a 300 µm long ridge waveguide laser is shown in Fig. 2. Recent structures achieves 20 mA threshold current for 600 µm long devices with cw room temperature output powers of about 15 mW from an uncoated facet at 80 mA [11] and are comparable with state-of-the-art 1.55 µm QW lasers with ridge waveguide geometry. In comparison to QW lasers, the temperature dependence of the emission wavelength can be much lower (0.2 nm/K instead of 0.55 nm/K), which allow the realization of single mode lasers, which can be operated over a much larger range of operation temperatures [11].

Distributed feedback lasers with laterally defined gratings reach modulation bandwidths beyond 7.5 GHz [13], which will make 10 GBit/s data transmission possible. Nevertheless, the bandwidth of quantum dots lasers in general is more limited in bandwidth than previously expected. The reason is based on inherent problems in carrier transport [14], especially the capture time is an important factor as well as the reduction of the spectral gain due to the inhomogeneous linewidth broadening. Possibilities to overcome these limitations will be discussed in Section 4.

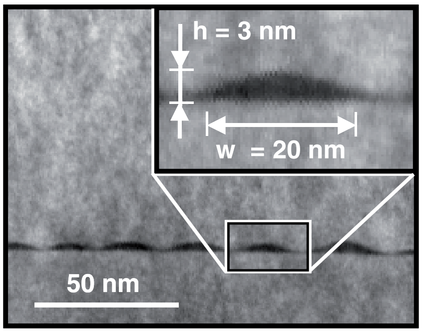

Fig. 1 XTEM image of overgrown QDash test sample perpendicular to the dashes. For the formation of the QDashes 5 ML InAs were deposited. The inset shows a magnification of a single QDash structure with the indicated dimensions [12].

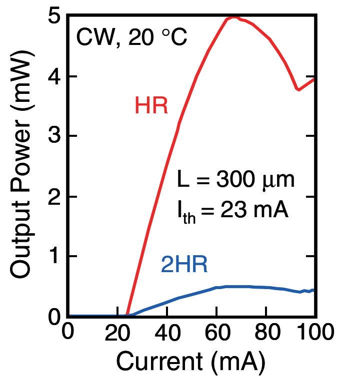

Fig. 2 (online colour at: www.pss-b.com) CW light output characteristics of a QDash laser of 300 µm cavity length. The plot indicated by HR is related to the front facet the plot indicated by 2HR to the higher reflecting back facet, respectively.

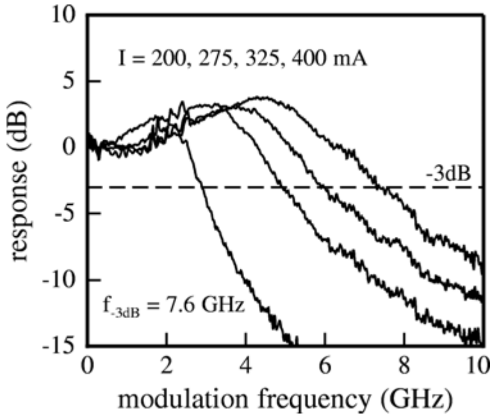

Fig. 3 Small signal modulation response for a QDash DFB laser at four different pulsed (10 μs pulses at a duty cycle of 2%) bias levels [14].

2.2 High speed semiconductor amplifiers

Although there are carrier transport limitations in high speed modulation of lasers, high speed optical signals can be much faster amplified in quantum dots optical amplifiers (QD-SOAs) than in conventional quantum well SOAs. This is due to the much faster recovery time caused by the local storage of carriers. In Fig. 4, the time response of a QDash-SOA is shown, which can be fit by a bi-exponential decay with a fast (ca. 1 ps) and a slower component (>100 ps) [15]. This behavior is different to 1.3 μm QD-SOAs and has to do with the wire-like nature of these quantum dots [16, 17]. More details are discussed in [18]. In comparison to the typical gain recovery time of MQW-SOAs of 100–200 ps related to carrier transport, QD-SOAs are about two orders of magnitude faster [19]. With a recently proposed approach based on two-photon absorption, also the residual capture time in QD SOAs might be reduced leading to further reduced pattern effects in high speed optical signal processing [20].

Due to the fast recovery time, QD-SOAs can amplify high bit-rate signals without signal distortion. 40 GBit/s amplification in deep saturation mode of the SOA could be already confirmed with improved signal to noise figures at 1.3 μm [21] and 1.5 μm [11].

Another big advantage of quantum dots systems for this application is the spatially distributed gain, which splits the inhomogenously broadened spectral gain into independent amplification regions, i.e., each dots ensemble excited within the homogeneous linewidth can amplify a signal independently from the others. This property can be used for multi-wavelength amplification and was the first time verified in QDash-SOAs [22]. In Fig. 5, the optical output spectrum for 8 simultaneously amplified 10 GBit/s signals can be seen. No significant cross-talk between the different channels can be observed for this

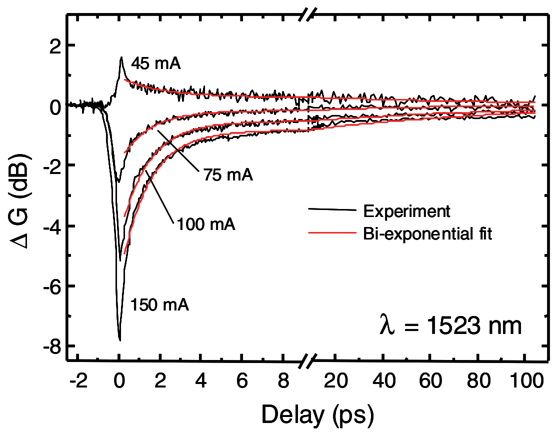

Fig. 4 (online colour at: www.pss-b.com) Time resolved spectra of the gain change in a QDash SOA at different drive currents. The test signal has a wavelength of 1523 nm and a pulse length of 150 fs [15].

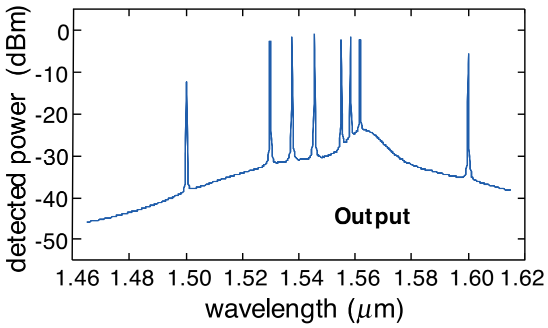

Fig. 5 (online colour at: www.pss-b.com) Optical output spectrum of a QDash SOA with 8 simultaneously amplified input signals at different wavelengths. An input power of –21 dBm was used for all 8 wavelengths. Each PRB signal is modulated at a data rate of 10 GBit/s. [22].

data-rate. In QW-SOAs this would be impossible, because each amplified wavelength would directly modify the carrier density for the other wavelengths ending in a strong cross-talk between all channels.

A drawback of the compact semiconductor amplifiers in comparison to fiber based amplifiers is usually the strong polarization dependence of the optical gain. However, very recently, it could be successfully demonstrated that polarization insensitive optical gain could be obtained in QD-SOAs by tailoring the dot shape [23].

3 High power quantum dots lasers

There are several interesting properties of QD materials for high power laser applications. One, e.g., is the reduced or zero linewidth enhancement factor, which can reduce the filamentation problem in broad area lasers, i.e., laterally unguided high power sources. Another more general aspect is the utilization of the additional free geometric parameters in quantum dots structures (dot density, dot size and size distribution), which allow to tailor the optical gain profile independently of the material composition. This can be used to stabilize the emission wavelength of high power lasers by an intrinsic temperature compensation effect [5] to avoid expensive external cooling by Peltier elements, e.g., for pump sources for fiber amplifiers or lasers with narrow absorption bands. This was first demonstrated at 980 nm [5, 24]. Recently such devices were realized with GaInAs/Ga(Al)As quantum dots laser structures emitting at 920 nm, which fits with a slightly broader absorption band of Yb doped fibers more suitable for coolerless pump applications. In the following some results are shown.

3.1 QD lasers for coolerless pump sources

In Fig. 6, photoluminescence (PL) spectra of different dots structures at 100 K are shown. By modifying the growth parameters and In composition, the average dot size can be reduced by keeping the emission wavelength of the fundamental transition constant. With the smallest dots a transition energy splitting of 65 meV can be obtained at a room temperature emission wavelength of about 920 nm [25].

A single quantum dot layer structure of type c in Fig. 6 was included into a high power laser design especially tailored for 920 nm emission. Broad area lasers were mounted epi-side down on a copper heat sink. In Fig. 7, the light output characteristics are shown for a 1 mm long as-cleaved device with 100 µm wide contact stripes. At a cw output power of 1.5 W a wall-plug efficiency of 55% could be obtained with a maximum output power of more than 3 W [25]. This quantum dot design of type c allows a very good internal temperature compensation of the emission wavelength shift with a coefficient of 0.09 nm/K, which is about a factor 3.5 less than for quantum well lasers (0.32 nm/K). Also high pulsed output powers of up to 7 W were achieved in 1.5 µm QD lasers grown on a metamorphic buffer on GaAs [26].

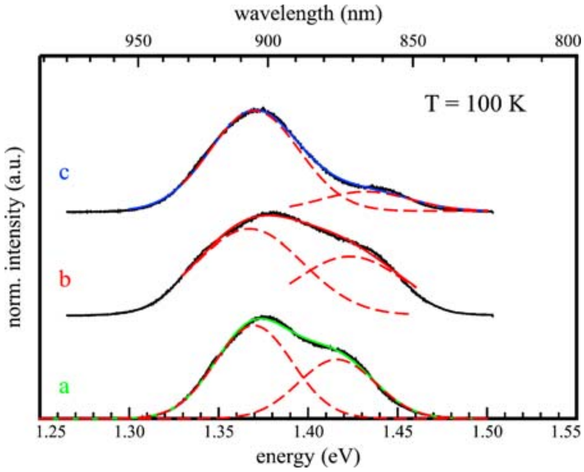

Fig. 6 (online colour at: www.pss-b.com) PL spectra of dot layers with different dot sizes resulting in different transition energy splittings between fundamental and first excited state transitions (a = 47 meV, b = 56 meV, c = 65 meV) [25].

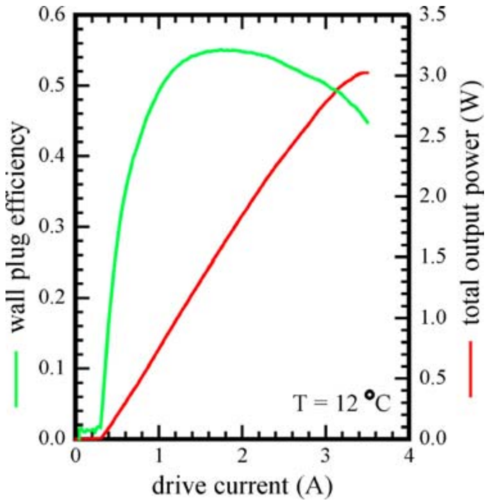

Fig. 7 (online colour at: www.pss-b.com) Total output power and wall-plug efficiency of a quantum dot high power laser with 1 mm cavity length and 100 µm broad contact stripes. The facets are cleaved without coatings. Maximum cw output power of 3.02 W and a maximum wall-plug efficiency of 55% at 1.5 W are obtained [25].

3.2 Single mode tapered lasers

Broad area lasers are in general multi-mode emitting devices. To obtain laterally as well as longitudinally single mode emission a different device geometry has to be used. In Fig. 8a sketch of a tapered laser with laterally defined feedback gratings is illustrated. Such lasers allow the amplification of a single lateral mode during the propagation through the tapered section while the grating selects a single longi-

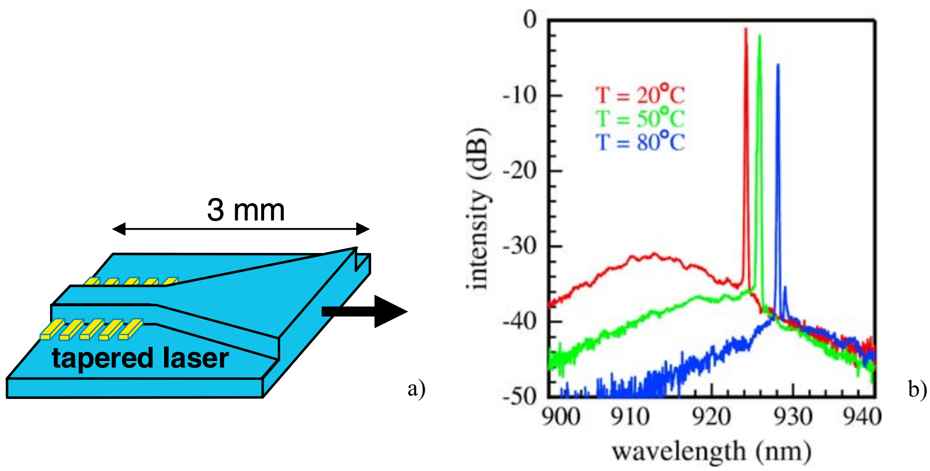

Fig. 8 (online colour at: www.pss-b.com) a) Sketch of a tapered laser design with laterally defined feedback gratings at the ridge section. b) Emission spectra for 3 different temperatures of a single mode emitting QD tapered laser are shown [27].

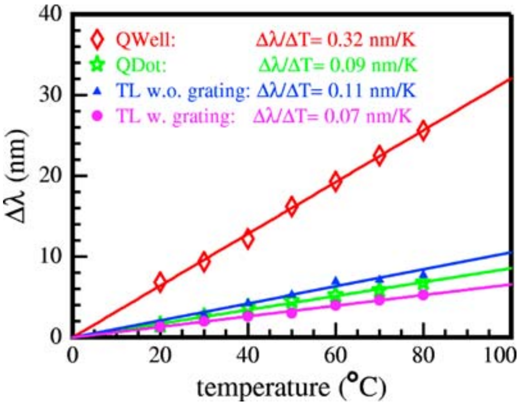

Fig. 9 (online colour at: www.pss-b.com) Comparison of the wavelength shift of tapered lasers (TL) with (solid dots) and without gratings (solid triangles) with a broad area quantum dot (stars) and quantum well lasers (diamonds) [27].

tudinal mode. Single mode emission spectra with 30 dB side-mode suppression are plotted in Fig. 8b. In addition, this grating further stabilize the emission wavelength due to the weaker temperature dependence of the refractive index. In Fig. 9, the wavelength shift of different devices are compared. With the tapered grating laser a temperature coefficient of 0.07 nm/K can be obtained, which is very near to the temperature dependence of tapered lasers without gratings. This is also important, because otherwise the gain function will not coincide with the Bragg wavelength of the grating and the laser emission would switch off. Therefore, this approach is only working over a larger temperature range by using quantum dot gain material with tailored properties.

4 Conclusions and prospects

Within the last couple of years specific properties of quantum dots structures were utilized to realize optoelectronic devices with unique features not possible with conventional approaches. Especially, the additional free geometric parameters in quantum dot layers allow to tailor the spectral gain profile appropriate to specific applications, like coolerless pump sources or multi-wavelength amplification in SOAs. However, this design freedom is limited due to technological restrictions. Within the next years it will be very important to widen the parameter range, e.g., to develop techniques to reduce the inhomogeneous linewidth broadening to a value comparable to the homogenous linewidth. Many groups are now working to improve the position and size control in self-organization processes by using surface preparation techniques. An improvement in these techniques, if it can be also applied in high density dot systems, will be the key issue in the future progress in quantum dots device applications.

Another very important issue would be to decouple the carrier capture from the escape process. Because the carrier capture process is a bottle neck in high excitation systems as lasers and limits the modulation bandwidth. A possible approach is to use tunnel injection into quantum dots via LO phonon scattering [28]. This would allow the injection of fatly cooled carriers into the recombination zone without loosing additional carriers by the thermal relaxation process within the dot. First experiments on tunnel injection quantum dots lasers for high power applications show in comparison to QW or pure QD lasers increased spectral gain at the fundamental transition energy by keeping the broad band characteristic of QD lasers [29]. It seems that with this approach the advantages of QW lasers, i.e. higher modal gain, and of QD lasers, i.e., dots related quantum effects, can be combined to tailor the material properties in a much wider range than possible with QD structures alone.

Both approaches, the improved control of dot formation process and of the carrier dynamics are extremely important for future device applications and can mark a break-even point for the commercialization of quantum dots optoelectronic devices by substituting QW lasers at least for specific applications.

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