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Recent advances in semiconductor quantum-dot lasers

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Abstract

Within the last few years a breakthrough in the device performance of quantum dot lasers occurred and new application areas were opened. Recent advances in the understanding and realisation of quantum dot lasers are reviewed. ***To cite this article: J.P. Reithmaier, A. Forchel, C. R. Physique 4 (2003).***

Résumé

Avancées récentes des lasers semiconducteurs à boîte quantique. Nous avons assisté ces dernières années à un progrès décisif dans la performance des lasers à boîte quantique, qui leur a ouvert tout un champ d'applications nouvelles. Les progrès récents dans la compréhension et la réalisation des lasers à boîte quantique sont passés en revue. ***Pour citer cet article : J.P. Reithmaier, A. Forchel, C. R. Physique 4 (2003).***

Keywords: Quantum dot laser; Inhomogeneous broadening; Wavelength stabilisation; Spectral gain; Narrow linewidth; High power laser; Self-assembled dots; Multi-wavelength amplification

Mots-clés : Laser à boîte quantique ; Élargissement inhomogène ; Stabilisation en longueur d'onde ; Gain spectral ; Largeur de raie ; Laser de haute puissance ; Boîtes auto-assemblées ; Amplification multi-longueur d'onde

1. Introduction

Since the introduction of quantum wells, theoretical studies have been performed to look for the ultimate use of quantum mechanical effects in semiconductor lasers. Arakawa and Sakaki pointed out that a laser material with quantum mechanical carrier confinement in all three dimensions, called quantum dots, could give rise to lasers with temperature independent properties [1]. Asada et al. showed very clearly that quantum dot like structures would allow a significant reduction of the threshold current density in comparison to quantum film based lasers [2]. However, it took more than one decade to improve the material quality of quantum dot structures to the device level. The breakthrough came a couple of years ago with the application of self-assembly techniques of quantum dots during the epitaxial growth process [3–5].

Further improvements have been achieved by embedding InAs dots within GaInAs layers [6,7] and by optimising the carrier confinement [8,9]. Low threshold current densities [10,11] and high output powers have been obtained for 980 nm [12] and 1.3 µm [13] emitting devices. As expected by theory, very high temperature stability of the threshold current density could be observed below room temperature [14,15]. Above room temperature the characteristic temperature (T_0 value) degrades significantly but laser operation beyond 200 °C could be already demonstrated [8].

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For telecommunication applications other material properties are of comparable importance such as high wavelength stability in cw- and small signal modulation operation. To stabilise the emission wavelength of Fabry–Perot lasers, distributed feedback gratings are used. Unfortunately, due to the large temperature shift of the gain maximum in comparison to the refractive index change, conventional DFB lasers can only be operated in a relatively limited temperature range of about 50 K. In quantum-dot lasers the temperature shift of the gain function is strongly reduced and allows stable single-mode emission over a much larger temperature range [16]. For high speed data transmission the wavelength has to be also very stable during intensity modulation. This aspect can be described by the linewidth enhancement or 'chirp' factor. As has been shown already in several experiments, this factor seems to be much lower in quantum-dot lasers [17,18] which makes this new material very promising for the realisation of high speed directly modulated lasers.

In this paper an overview of the recent advances in the understanding of some basic properties and improvements of device characteristics of quantum-dot lasers will be given: Examples for different application areas covering the wavelengths of 980 nm, 1.3 µm and 1.55 µm will be presented and discussed. While the longer wavelength material is clearly dedicated to telecom applications the shorter wavelength material is interesting for high power and sensor applications as well as for optical data processing.

2. Basic quantum dot and laser properties

2.1. Discrete energy levels

One major advantage of quantum dot structures results from the full three-dimensional carrier confinement on a nanometer scale. Therefore, semiconductor quantum dots, e.g., InAs dots embedded in GaAs, behave like non- or weakly interacting single atoms. They show a discrete energy spectrum with splitting energies controlled by the geometric size. From the discretization of the energy spectrum one can directly deduce a high density of states at the emission energy of the laser, which is much higher than in bulk or quantum well material. Therefore, a significant reduction of the threshold carrier density in quantum dot lasers can be achieved. As an example, the modal gain of a QW (open dots) and QD (solid dots) laser material, respectively, is compared as function of the current density [11] in Fig. 1. Both lasers are emitting at about 980 nm at 20 °C and have the same vertical waveguide design. The values are evaluated from cavity length dependent measurements of the threshold current density. For comparison, the internal absorption of 2.2 cm^{-1} is plotted as dashed line. Due to the about one order of magnitude reduced active volume, the modal gain of a QD laser with a single layer of quantum dots is much lower at higher pump current densities in comparison to the QW laser. However, the threshold condition in QD lasers can be already satisfied at much lower current densities and is mainly limited by the intrinsic absorption while for QW lasers the minimal threshold current density is generally limited to about 60 A/cm^2.

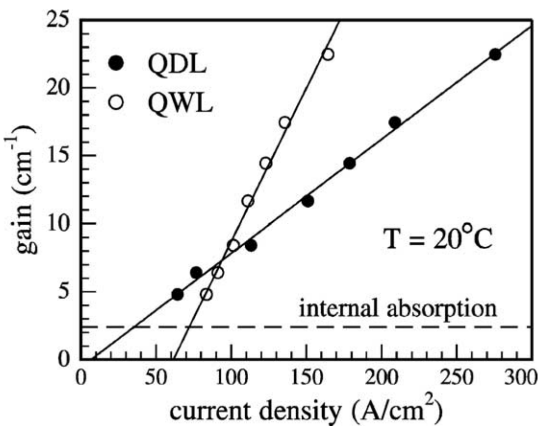

Fig. 1. Modal gain of a QW (open dots) and a QD laser (solid dots) as function of the current density. The values were evaluated from threshold measurements of 100 µm wide broad area lasers with variable cavity lengths.

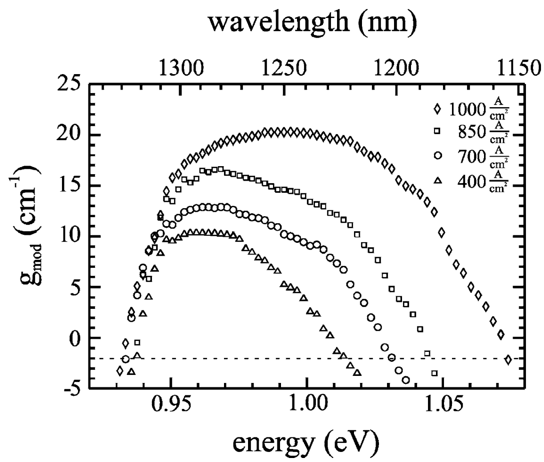

Fig. 2. Gain spectra of a 1.3 µm InAs/GaAs QD laser with 6 stacked DWELL layers for different current densities. The spectra were determined by subthreshold electroluminescence measurements for different current injection lengths. The internal absorption of the laser structure of $-2\ cm^{-1}$ is indicated as a dashed line.

2.2. Inhomogeneous broadening and spectral gain function

In real quantum dot structures, fabricated by self-assembly techniques, the size of the quantum dots fluctuates significantly. Therefore the discrete energy levels of a single quantum dot are broadened within a dot ensemble. However, the size fluctuations can be controlled within a certain extent by growth parameters and can be used as an additional degree of freedom. As a direct consequence of the transition energy broadening, quantum dot material shows a much larger gain bandwidth than quantum well material. In Fig. 2, the spectral gain function of a 1.3 μm emitting QD material is plotted for different current densities [19]. The gain of the first transition saturates already at low current densities and is getting more flat at higher current densities due to the contribution of the two-fold degenerated next higher order transition. Therefore, a flat gain profile over more than 100 nm can be obtained, which is about 3 times more than in quantum wells. Nevertheless, the threshold current densities are still significantly lower than in QW lasers.

The combination of dot density, size fluctuations and discretization of energy states allows one for the first time to design the spectral gain profile in an amplifying material by geometric parameters. As a consequence, material properties like saturation

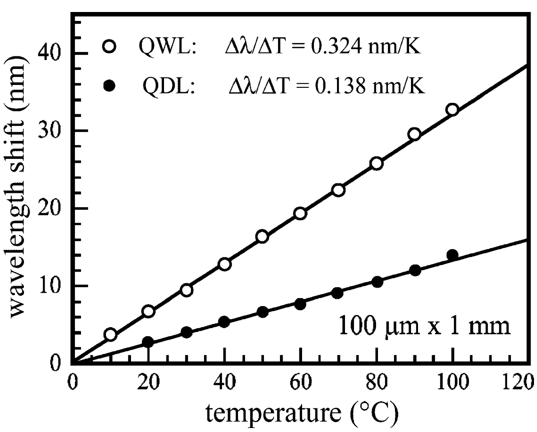

Fig. 3. Shift of the emission wavelength as function of the operation temperature of 100 μm wide broad area GaInAs/GaAs QW (open dots) and QD lasers (solid dots). The emission wavelength for both devices is about 980 nm. The solid lines are linear fits of the data points.

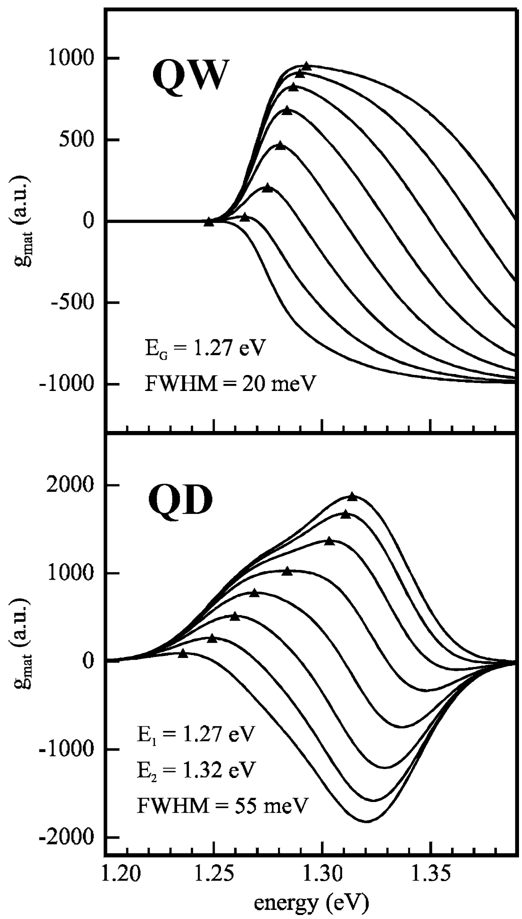

Fig. 4. Calculated material gain for different quasi-Fermi levels, i.e., different carrier densities, in case of a QW (top) and QD active layer (bottom). The quasi-Fermi level was varied between 1.25 to 1.39 eV in both cases. The transition energies in both cases are identical, but for the inhomogeneous broadening at room temperature a linewidth of 20 meV for QWs and 55 meV for QD states were used. For the splitting energy of QDs a value of 50 meV was assumed comparable to real 980 nm GaInAs dots.

gain, state filling behavior and temperature dependence of threshold condition and emission wavelength can be tailored by intrinsic material properties.

2.3. Wavelength stabilisation

As an example, the temperature dependence of the emission wavelength of a 980 nm emitting QW (open dots) and QD laser (solid dots) are plotted in Fig. 3. By a specific design of the quantum dot geometry in combination with an appropriate optical confinement factor, the temperature dependence of the emission wavelength can be reduced by nearly a factor of 2.5 in comparison to QW lasers [20]. The reason for the much lower temperature dependence of the emission wavelength is based on the state filling behavior which can be tailored in a way that the temperature dependent bandgap shrinkage of the material can be significantly compensated [21]. To illustrate this basic effect, the spectral gain functions are plotted in Fig. 4 for different carrier densities in the case of a QW (top) and a QD structure (bottom) [22]. For the QD structure, only the fundamental and next higher order transitions are taken into account and a Gaussian line shape broadening was assumed. Due to increased state filling the gain maximum shifts to higher energies at higher carrier densities. While the energy shift is weak in case of the QW structure due to the high modal gain, the energy shift in case of the QD structure is especially strong near the flat intermediate range between the two transitions. The slope of the gain profile can be tailored by the splitting energy and the inhomogeneous broadening. The operation point within the gain function can be fixed by the optical confinement factor, because the optical confinement factor controls the modal gain and the saturation behavior of the material. Nearly optimum conditions were already achieved in InP based QD material [23]. In Fig. 5, the temperature dependence of the emission wavelength is shown for QD (solid diamonds) and QW laser material (open dots). In this case, the temperature coefficient of QD material is by about a factor of 4.4 lower than for QWs and is already nearly as low as the refractive index change by temperature.

2.4. Multi-wavelength amplification

Much progress was made in last few years in the understanding of the principles of quantum-dot lasers. First, the explanation for the turn-on of lasing was quite contradictory. By assuming an ideal case of delta-function-like quantum dot transitions only a few dots could contribute to the lasing process. The final modal gain of a quantum dot layer was explained by a very high material gain. But this is in contradiction with the fundamental fact that the oscillator strength of a material should be in a zero-order approximation proportional to the number of involved atoms which would be quite low in the case of only a few quantum dots.

On the other hand it was observed that QD lasers operated at low temperature show a very broad multi-wavelength emission in agreement with a narrow homogeneous linewidth of <0.1 meV while at room temperature the spectrum is quite narrow [24]. This spectral narrowing effect at room temperature requires a much broader homogeneous linewidth in the order of 10 meV as calculations show. This homogeneous linewidth broadening could be indeed confirmed by single-dot spectroscopy and the determined linewidth of 12 meV at 300 K could be explained mainly by scattering of electrons with LO phonons [25]. Due to this broadening of the homogeneous linewidth, about 20–30% of all dots will contribute to the lasing operation by electromagnetic

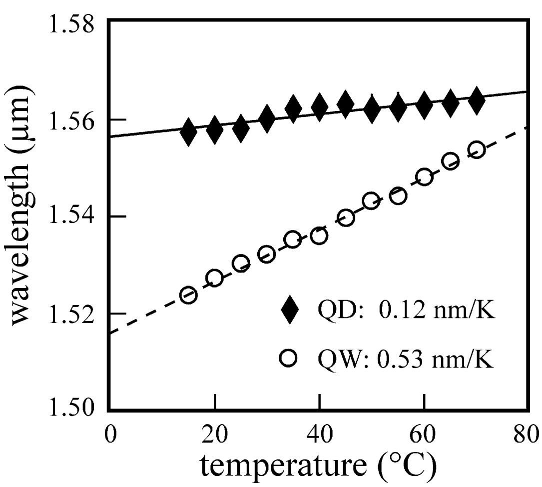

Fig. 5. Comparison of the temperature dependence of the emission wavelength of InP-based QD (diamonds) and QW lasers (open dots). The solid and dashed lines are linear fits to the data points.

coupling of the propagating wave. Nevertheless, the spectral gain function is, at room temperature, still split into separated gain regions which should allow multi-wavelength amplification in contrast to QW material.

2.5. Carrier diffusion, bandgap absorption and linewidth enhancement factor

In addition, there are further important aspects which make quantum dot gain materials especially attractive for semiconductor lasers. In the quantum well case, due to translation symmetry in the plane, the recombination position is not fixed. As the quantum dots provide lower energy states for the electrons and holes than the surrounding material the recombination occurs localised at the dot positions. This localisation effect has important consequences for a variety of material properties like a reduced carrier diffusion length, a strongly reduced interaction of carriers during the energy dissipation process to the lasing states etc. It also results in a reduced active laser volume. The last item leads already to a lower transparency carrier density in addition to the threshold improvement caused by the higher density of state function in quantum dot structures as discussed above.

As a consequence of these geometric effects one would also expect further application-relevant improvements. For example a reduction in leakage currents to surface states is expected due to the reduced lateral diffusion length, a lower band edge absorption due to the reduced active volume, and a reduced linewidth enhancement factor ($\alpha = -4\pi/\lambda \times (\mathrm{d}n/\mathrm{d}N)/(\mathrm{d}g/\mathrm{d}N)$). The reduced α-factor is partially related to a more symmetric gain function, but also caused by a weaker interaction of the electromagnetic wave with localised carriers in the dots [26] in comparison to QW structures. The α-factor is very important for wavelength stable high frequency modulation of telecommunication lasers and for the onset of filamentation effects in high power lasers [27].

2.6. Dynamic properties

At the beginning of the investigation of quantum dot structures, the so-called 'phonon-bottle neck' was discussed as a major limiting factor for fast relaxation into the ground states of quantum dots. In real structures it turned out that no 'phonon-bottle neck' exists and efficient LO-phonon scattering is present at room temperature (cf. discussion above about homogenous linewidth) [28]. Nevertheless, carrier transport in quantum dot structures is still an issue and is for the moment limiting the time response of high speed modulated lasers. Small signal modulation frequencies in the range of 10 GHz or below were reported which is significantly lower than maximum values obtained for QW lasers. Several new approaches address the problem of inefficient carrier transport. Very promising ideas are based on efficient carrier tunnelling via a QW layer into a dot layer [29] or by local p-doping in the active region [30], which avoid in general the slow hole transport. Both approaches increase the recombination probability and improve the temperature stability of the laser threshold condition at room temperature. As a consequence, T_0-values of 160 K up to 80 °C were obtained [30] and high frequency modulation speeds of more than 20 GHz were proposed [31].

Quantum dot structures are also very interesting for semiconductor optical amplifiers (SOAs). The major problems of conventional amplifiers based on volume or quantum film material are the long recovery time due to slow hole capture and the fact that only one wavelength can be amplified due to fast relaxation times in the conduction and valence bands. Both aspects can be solved by quantum dot structures. The multi-wavelength amplification issue was already addressed above. Due to the local storage of carriers either in the quantum dots themselves or in continuum states of the wetting layer, the material has a much faster response than quantum film structures. Although, a first principle model is not existing so far, a fast gain recovery in quantum dots was predicted for SOAs [32] and already confirmed in semiconductor optical amplifiers [33,34].

3. Growth of self-assembled quantum dots

The highest quality quantum dot materials were achieved by self-assembly techniques based on metal organic vapour phase epitaxy (MOCVD) or molecular beam epitaxy (MBE). With etching and overgrowth techniques, as used previously, no comparable optical quality has been obtained so far. All quantum dot structures presented in the following were grown by MBE. However, for each specific wavelength range, different material systems and different growth procedures were applied. Quantum dot structures emitting at 1 µm and 1.3 µm were realised on GaAs substrates. Quantum dot structures for longer wavelengths in the range >1.5 µm were grown by gas source MBE on InP substrates.

While for 1 µm emission wavelength the best optical quality and best laser results were achieved with $Ga_{04}In_{0.6}As$ quantum dots (QD) embedded in GaAs [8,11], the dots-in-a-well (DWELL) concept [6] was used for 1.3 µm emitting material. Here InAs QDs were embedded in a strained GaInAs quantum film with typical 15% In content grown on GaAs [19,35]. The dot density for the shorter wavelength material is in the range of 2×10^{10} cm^{-2}, while for the longer wavelength material more than 5×10^{10} cm^{-2} were achieved. Nevertheless, the gain in the 1 µm material is nearly one order of magnitude higher than for the

1.3 µm material. Therefore, a single quantum dot layer has sufficient gain to drive a 1 µm quantum dot laser. For 1.3 µm quantum dot lasers a stack of 3–8 quantum dot layers is necessary to achieve conventional device lengths of less than 1 mm. A recent improvement could be achieved by an asymmetric DWELL design [36], which allows a more homogenous dot size distribution and smaller dots. Due to the improved dot geometry, the spectral linewidth decreases and the splitting energy increases. As a consequence, the transparency current density decreases significantly and the temperature stability increases. Without p-doping a T_0 value of 130 K could be obtained up to an operation temperature of 50 °C [36].

For InP based quantum dot structures, InAs was deposited on AlGaInAs lattice matched to InP. Due to the reduced lattice mismatch between InAs and InP (half the value of InAs on GaAs), the formation of quantum dots on InP strongly differs from the GaAs material system. On (001) oriented InP, more wire like structures with finite lengths were formed preferentially aligned in [0-11] crystal direction [37,23]. The density of such quantum dashes is quite high and the material gain is significantly higher in comparison to 1.3 µm quantum dots. Because this material system is quite new, many fundamental properties are still under investigation. Nevertheless, this new material seems to be more quantum dot like in terms of gain properties than the morphology looks like [23]. This may be caused by the fact that mainly larger islands work as the real recombination zones while the narrower short wires act more like capture channels which feed the larger quantum dots.

4. Device properties

In the following, device examples are chosen to highlight a few important future application areas, where quantum dot devices can play an important role.

4.1. 980 nm High-power quantum-dot lasers

Due to a low linewidth enhancement factor, a flat gain profile and lower temperature sensitivity, quantum dot lasers are also interesting for high power applications. In Fig. 6, the light output characteristic of a 980 nm quantum dot laser is shown in continuous wave (cw) operation at room temperature. The device is mounted with epi-side down on a copper heatsink. The cleaved facets are uncoated. A maximum total output power of more than 5 W was obtained. Such lasers can be operated in cw up to more than 110 °C with output powers exceeding 1 W and wall-plug efficiencies above 50% [12]. These data are already comparable to high performance high power QW lasers. The main direction for further development would be to improve specific dot related properties, like, e.g., improved beam quality in high-brightness applications and stable emission wavelength for uncooled high power devices. Also the enlargement of the operation temperature range of DFB lasers by using QD material with a temperature stabilised and broadened gain profile [16] would be favourable for, e.g., sensor applications.

4.2. 1.3 µm Telecommunication quantum-dot lasers

For telecommunication lasers, single mode emission is necessary. Laterally coupled metal gratings, as shown in Fig. 7, are used to fabricate DFB lasers after conventional ridge waveguide processing [19]. In Fig. 8, the light output characteristic of a DFB laser with an emission wavelength of 1.27 µm is shown. With the recent generation of QD laser material a very low cw threshold current of 9 mA was achieved for a cavity length of 800 µm.

4.3. 1.55 µm Quantum-dash lasers

The major wavelength range for telecommunication lasers is in the 1.55 µm range. QD lasers based on GaAs substrates are up to now not realised, although they might be feasible. An alternative approach for this wavelength range are InP based QD lasers. In Fig. 9, the recent results of broad area lasers with different cavity lengths are shown. For a cavity length of 1.3 mm a threshold current density of about 800 A/cm^2 was achieved for uncoated devices [38]. This value is already comparable to high quality GaInAsP QW laser material. The inset of Fig. 9 shows the emission wavelengths of two lasers with different quantum dash thicknesses. Here, the shorter wavelength material at 1.54 µm is grown by depositing 5 MLs InAs while the longer wavelength material at 1.78 µm is grown by depositing 7.5 MLs InAs. This illustrates the wide wavelength range, which can be easily covered with the same material system.

A large interest in this material is in the realisation of SOA devices. First SOAs were fabricated and show first promising results [39] with properties comparable to quantum dot material based on GaAs substrates.

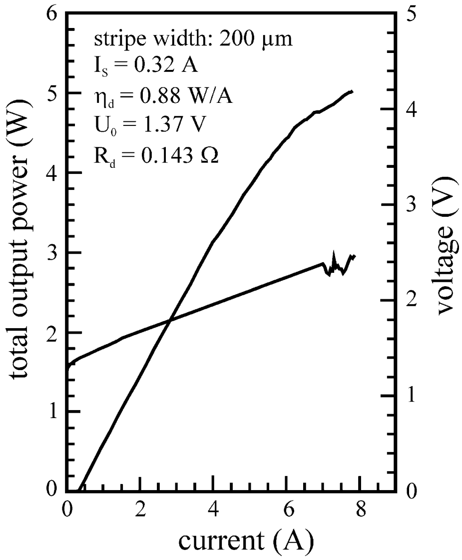

Fig. 6. Device characteristics of a 980 nm GaInAs/GaAs QD laser in cw operation at room temperature. The stripe width is 200 µm. The cleaved facets are uncoated. The device is mounted epi-side down on a copper heat sink.

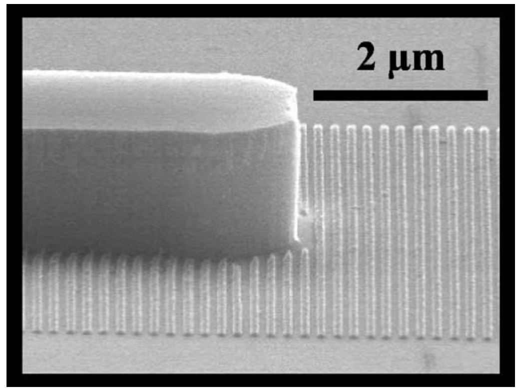

Fig. 7. SEM image of a laterally coupled 1.3 µm QD DFB laser before planarisation and metallisation. The metal grating has a period of 193 nm. The ridge width is 3.5 µm.

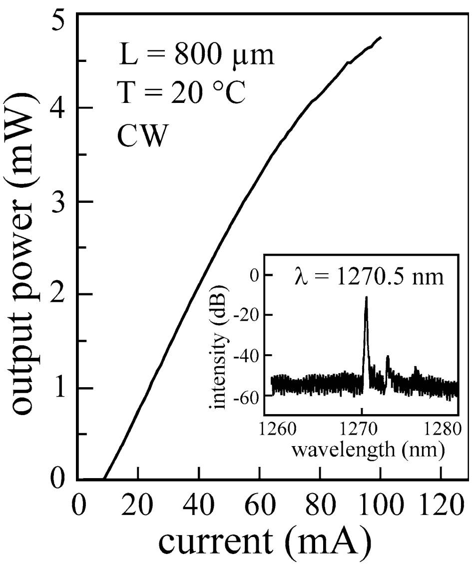

Fig. 8. Light output characteristic of 1.3 µm QD DFB laser with AR/HR coated facets. The cavity length is 800 µm. The threshold is below 9 mA. The inset shows the emission spectrum at room temperature.

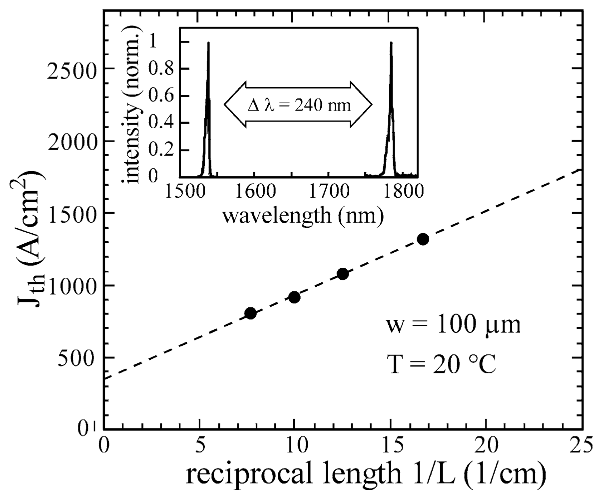

Fig. 9. Threshold current density as function of the reciprocal cavity length of an InP-based quantum dash laser with an emission wavelength of 1.55 µm. The measurements were made on 100 µm wide broad area lasers in pulsed mode. The inset shows the emission wavelength of two quantum dash lasers with different dash sizes controlled by the number of deposited monolayers (see text).

5. Conclusions

Much progress has been made in the last couple of years by improving the material quality and by introducing new design concepts. The device performance is in many application areas comparable to best QW lasers, e.g., 980 nm high power lasers, 1.3 µm DFB lasers and 1.55 µm InP-based lasers. Also the use of QD gain material for semiconductor optical amplifiers is very promising and could be demonstrated at the 1.3 and 1.55 µm wavelength ranges.

Due to a much better understanding of the laser principles and of the influence of the dot geometry on the device performance, one is now able to tailor specific laser properties, such as the spectral gain profile, the temperature dependence of emission wavelength and the threshold current density. Further improvements in the understanding, as well as in the realisation, are necessary in the dynamic properties. Here, the role of the interaction between continuum states and discrete energy states in the dots as well as phonon scattering have to be investigated in more detail. However, new approaches, such as tunnelling injection and p-doping, might allow us to overcome the present limitations in high speed modulation of QD lasers very soon.

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