Performance of quantum-dot-based tunnel-injection lasers: A theoretical analysis

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Tunnel-injection lasers promise advantages in modulation bandwidth and temperature stability in comparison to conventional laser designs. In this paper, we present results of a microscopic theory for laser properties of tunnel-injection devices and a comparison to a conventional quantum-dot laser structure. In general, the modulation bandwidth of semiconductor lasers is affected by the steady-state occupations of electrons and holes via the presence of spectral hole burning. For tunnel-injection lasers with InGaAs quantum dot emitting at the telecom wavelength of 1.55μm, we demonstrate that the absence of spectral hole burning favors this concept over conventional quantum-dot based lasers.

I. INTRODUCTION

Semiconductor laser devices are important components for fiber-optical communication. Requirements for optoelectronic applications include low threshold current, high temperature stability, and large modulation bandwidth. In conventional quantum dot (QD) laser devices, the pump process generates carriers in delocalized states, while the QD ground state is used for the carrier recombination into the laser mode.

Tunnel injection devices have been proposed to enhance both temperature stability and modulation properties. The latter are limited by hot carrier effects, a problem that the tunnel injection scheme is designed to overcome by feeding cold carriers from an injector well (IW) directly to the optically active QD states. This concept has been demonstrated for QDs and quantum well systems. In recent experiments with devices utilizing the TI scheme improvements of GaAs-QD based high-power lasers and ultra-fast gain recovery have been achieved. Despite these successes, open questions remain regarding the design requirements. To which extent needs the LO-phonon resonance to be considered in the level alignment? What is the role of non-equilibrium carrier effects? What are suitable designs to suppress hot carrier effects? To address these points we provide a theoretical analysis that connects the electronic states and carrier scattering processes on one hand and the resulting laser properties such as temperature stability and modulation bandwidth on the other hand.

In an earlier publication, we discussed the physics of carrier scattering in tunnel injection structures. When the design leads to hybridized states between IW and QD, this significantly enhances the carrier capture into the laser levels. In this work, we analyze the laser properties of TI devices on a microscopic footing and discuss the advantages of the TI design. On a general level it is known that the temperature dependence of the laser threshold is influenced by the temperature dependence of the carrier scattering. We show for the TI system that the carrier scattering is rather insensitive to temperature in the investigated parameter range, which in turn improves the temperature stability of the laser emission.

Additionally an enhanced hole occupation of the IW

FIG. 1. (a) Band structure of a TI QD device with the IW separated by a thin barrier from the QDs that provide the laser level. Process 1 and 2 (red arrows) describe the capture of conduction band electrons from the bulk states into the IW and the relaxation from the hybridized IW-QD state into the optically active QD ground state, respectively. (b) DWELL structure used for comparison. The QD emits at the same wavelength. Here, the carrier dynamics is determined by the capture from the bulk into the QW, followed by capture from the QW into the QDs and intra-QD relaxation.
FIG. 2. Steady state properties of the DWELL and two different TI lasers. (a) Input-Output characteristics for the DWELL structure (black) and TI devices with QD sizes of 16x24nm (green) and 16x32nm (red), respectively. Dimensions refer to the in-plane extensions of ellipsoidal QDs. (b) Temperature dependence of these three devices for a temperature range of 300K-350K. The parameter $T_0$ stems from an exponential fit of the temperature dependent threshold current (see text).

improves temperature stability in a similar manner to p-doping of conventional QD laser structures.\(^\text{12}\) We find that a main limiting factor of the small signal modulation bandwidth is spectral hole burning, that leads to a strongly nonlinear gain. In TI devices this spectral hole burning is largely suppressed, as the carrier dynamics is fast enough to ensure sufficient carrier supply into the optically active states due to the high density of states in the IW and the efficient hybridization of IW and QD states. The latter provides enhanced carrier scattering to sustain a quasi-equilibrium situation, even under laser operation conditions.

II. RESULTS

To assess the advantages of TI lasers, we perform a comparison to a conventional QD-based laser design in the form of a dot-in-a-well (DWELL) structure. As shown in previous work\(^\text{9}\), the design of the QDs can affect the hybridization strength and hence the efficiency of carrier scattering. Therefore two different QD geometries for the TI devices are considered, one with moderate (16x24nm) and one with near-optimal (16x32nm) hybridization strength. These geometries are within the size distribution recently found in HRTEM investigations of TI-QD laser devices.\(^\text{13}\) For the comparison, we ensure that both TI and DWELL structures operate at the same emission wavelength (1550nm) and closely resemble devices currently under experimental investigation.

As described in the supporting information, the corresponding band-structures are shown in Fig. 1, obtained from $\vec{k} \cdot \vec{p}$ theory using the nextnano 3 package.\(^\text{14}\) The band-bending near the QD and IW results from the included strain field. The small edge of the potential next to the QD represents the wetting layer, which, however, carries no bound states due to its small thickness. For details of our theoretical model we refer to the supporting information. In Fig. 2(a) input-output characteristics for DWELL and TI structures are shown. To focus our comparison on the changes inherent to the TI design, we use the same non-radiative decay rate in both systems. Under this assumption, we find a factor of 2 lower threshold current for the DWELL device. For our comparison, the excited carrier population of the TI well is somewhat larger than that of the DWELL continuum states as a result of the energetic distance to the QD laser levels. Assuming the same non-radiative rate, this introduces stronger non radiative losses for the TI structure. We emphasize that this outcome is specific for this type of comparison. In general, the actual non-radiative losses in particular devices have a stronger influence than the differences between TI and DWELL.

In Fig. 2(b) the temperature dependence of the threshold current is analyzed. The $T_0$ values stem from a fit with the exponential dependence $I_{th}(T) = I_0 \exp \frac{T}{T_0}$ and are in good agreement with those found experimentally for TI devices.\(^\text{3,4}\) Both TI devices clearly show superior temperature stability compared to the DWELL device. The carrier scattering via the hybridized state in the TI structure is much less temperature sensitive than in the DWELL structure, where the relaxation into the lasing state occurs via a cascade (process 2 in Fig 1 (b)). We also find that the temperature stability of the TI device with near-optimal hybridization conditions (16x32nm) surpasses that of the TI laser with moderate hybridization (16x24nm) Additionally, similar to the discussion in Ref.\(^\text{12}\), the temperature changes of the gain in high-population scenarios are reduced.
FIG. 3. (a) 3dB modulation frequency as function of current for all three devices. The color coding corresponds to Fig. 2. (b) Modulation response spectra for the 16x32nm QD device and three different currents as marked in (a). (c) Electron (top row) and hole (bottom row) populations for the current with the maximum 3dB frequency for the DWELL structure (left column), the 16x24nm TI structure (middle column) and the 16x32nm TI structure (right column). The solid lines denote the occupation function of the continuum of states, while the crosses show the QD occupations. Thermal distributions for the electrons are depicted as guide to the eye by the blue lines.

As a figure of merit for the modulation performance of the laser devices, the 3dB-bandwidth is provided in Fig. 3(a). Both TI structures clearly outperform the DWELL structure by a factor of 2 for moderate hybridization efficiency (16x24nm) and by a factor of 3 for near-optimal hybridization conditions (16 x 32nm). For all devices, the modulation bandwidth shows a distinct maximum about an order of magnitude above threshold current and is reduced significantly for higher injection currents. To understand this decrease, individual modulation spectra are shown in Fig. 3(b). For high currents the damping of relaxation oscillations is increased by an increase in carrier scattering rate, leading to a decrease in the 3dB bandwidth. This behavior is analogous to the situation found in QD-based nanolasers.

To analyze the origin of the higher modulation speed of TI structures, we show in Fig. 3(c) the electron and hole occupations for the maximum 3dB frequency of the respective device. In the DWELL structure (left panel) a distinct non-thermal behavior for the electrons due to spectral hole burning is observed. As a result, for the maximum of modulation speed the carrier supply into the lasing state is insufficient. In contrast, for the TI structures the electron populations are much closer to a
FIG. 4. Electron (left) and hole (right) populations as function of energy for the injection current with maximal modulation bandwidth (grey dashed line) and at a higher injection current (red solid line). The crosses denote the QD populations. The injection currents correspond to labels (2) and (3) in Fig. 3(a). The results are obtained for the 16x32nm TI structure.

In Fig. 4 we analyze the decrease of modulation bandwidth with increasing current further by showing the population functions for QD and IW states at the maximum of the modulation speed and at an elevated current as depicted in Fig. 3(a) by labels (2) and (3), respectively. At the maximum of modulation the carrier distribution for the electrons in the IW is nearly thermal which is indicative of sufficient carrier supply.

For an increased current the populations become non-thermal, as the QD population has a much lower value than the energetically higher lying continuum. This is indicative of pronounced spectral hole burning. As for the DWELL structure (cf. Fig. 3(c)) this non-thermal population is connected with an increase of gain nonlinearity and a loss of modulation bandwidth. The dip in electron occupation near the IW band edge marks the energy for which the strongest hybridization and hence the most efficient carrier scattering occurs. As before, the non-thermal character leads to a significant degradation of the 3dB bandwidth.

This result also illustrates a deviation from quantum well or bulk laser devices. In the QD-based lasers investigated here, the total carrier density does not clamp with injection currents above the threshold current. While the clamping is observed approximately for the optically active state, the density in the delocalized continuum states continues to rise with increasing injection current. Hence also detrimental effects like non-radiative decay, that depend on the total carrier density rather than on the carrier density within the QD ground state increase above threshold.

III. CONCLUSION

In this work, we have investigated the physical mechanism behind the increased temperature stability and modulation bandwidth of TI-based lasers. We find that the increase in temperature stability is governed by carrier scattering being less temperature dependent in the TI structures compared to the DWELL device. The modulation bandwidth is enhanced in comparison to conventional QD laser devices as the TI scheme is able to provide sufficient carrier supply to sustain a quasi-equilibrium situation without significant spectral hole burning. Our results show that the bandwidth can be increased by designing the QD and IW in a way that hybridization is efficient. We do not find any evidence of a necessity to tune the energy levels to the LO-phonon energy.

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1 P Bhattacharya and S Ghosh. Tunnel injection in 0.4 ga 0.6 as/gaas quantum dot lasers with 15 ghz modulation bandwidth at room temperature. *Applied Physics Letters*, 80(19):3482–3484, 2002.

2 S Fathpour, P Bhattacharya, S Pradhan, and S Ghosh. Linewidth enhancement factor and near-field pattern in tunnel injection in/sub 0.4/ga/sub 0.6/as self-assembled quantum dot lasers. *Electronics Letters*, 39(20):1443–1445, 2003.

3 P. Bhattacharya, S. Ghosh, S. Pradhan, J. Singh, Z.-K. Wu, J. Urayama, K. Kim, and T. B. Norris. Carrier dynamics and high-speed modulation properties of tunnel injection ingaas-gaas quantum-dot lasers. *IEEE Journal of Quantum Electronics*, 39(5):952–962, 2003.

4 Sishir Bhownick, Md Zunaid Baten, Thomas Frost, Boon S Ooi, and Pallab Bhattacharya. High performance inas/in0.53ga0.27as/23ala0.24as/inp quantum dot 1.55µm tunnel injection laser. *IEEE Journal of Quantum Electronics*, 50(1):7–14, 2014.

5 Emil-Mihai Pavelescu, C Gilfert, Johann P Reithmaier, A Martin-Minguez, and Ignacio Esquivias. High-power tunnel-injection 1060-nm ingaas-(al) gaas quantum-dot lasers. *IEEE Photonics Technology Letters*, 21(14):999–1001, 2009.

6 Pallab Bhattacharya, J Singh, H Yoon, Xiangkun Zhang, A Gutierrez-Aitken, and Yeeol Lam. Tunneling injection lasers: A new class of lasers with reduced hot carrier effects. *IEEE journal of quantum electronics*, 32(9):1620–1629, 1996.

7 X. Zhang, A. Gutierrez-Aitken, D. Klotzkin, P. Bhattacharya, C. Caneau, and R. Bhat. 0.98-/spl mu/m multiple-quantum-well tunneling injection laser with 98-ghz intrinsic modulation bandwidth. *IEEE Journal of Selected Topics in Quantum Electronics*, 3(2):309–314, 1997.

8 Jaroslaw Pulka, Tomasz Piwonski, Guillaume Huyet, John Houlihan, E Semenova, A Lematre, Kanel Merghem, Anthony Martinez, and Abderrahim Ramdane. Ultrafast response of tunnel injected quantum dot based semiconductor optical amplifiers in the 1300 nm range. *Applied Physics Letters*, 100(7):071107, 2012.

9 Stephan Michael, Michael Lorke, Marian Cepok, Christian Carmesin, and Frank Jahnke. Interplay of structural design and interaction processes in tunnel-injection semiconductor lasers, 2018.

10 T. B. Norris, K. Kim, J. Urayama, Z. K. Wu, J. Singh, and P. K. Bhattacharya. Density and temperature dependence of carrier dynamics in self-organized ingaas quantum dots. *Journal Physics D: Applied Physics*, 38(13):2077–2087, 7 2005. ISSN 0022-3727. doi:10.1088/0022-3727/38/13/003.

11 P. Blood, S. Colak, and A. I. Kucharska. Temperature dependence of threshold current in gaas/algaas quantum well lasers. *Applied Physics Letters*, 52(8):599–601, 1988. doi:10.1063/1.99647.

12 P. M. Smowton, I. C. Sandall, D. J. Mowbray, Hui Liu, and Matthew N Hopkinson. Temperature-dependent gain and threshold in p-doped quantum dot lasers. *IEEE Journal of Selected Topics in Quantum Electronics*, 13:1261–1266, 2007.

13 Marco Schowalter. private communication.

14 *nextnano*³ code, TU Munich (WSI), see http://www.nextnano.de/nextnano3/

15 L.A. Coldren and S.W. Corzine. *Diode Lasers and Photonic Integrated Circuits*. Wiley, New York, 1995.

16 A. Abdollahinia, S. Banyoudheh, A. Rippien, F. Schmabel, O. Eyal, I. Cestier, I. Kalifa, E. Mentovich, G. Eisenstein, and J.P. Reithmaier. Temperature stability of static and dynamic properties of 1.55 mum quantum dot lasers. *Opt. Express*, 26(5):6056–6066, Mar 2018. doi:10.1364/OE.26.006056 URL http://www.opticsexpress.org/abstract.cfm?URI=oe-26-5-6056

17 M. Lorke, T. R. Nielsen, and J. Mørk. Switch-on dynamics of nanocavity laser devices. *Applied Physics Letters*, 99(15):151110, 2011. ISSN 00036951. doi: DOI:10.1063/1.3651765 URL http://dx.doi.org/10.1063/1.3651765