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Berg, Tommy Winther; Bischoff, Svend; Magnúsdóttir, Ingibjörg; Mørk, Jesper

Published in:
I E E E Photonics Technology Letters

Link to article, DOI:
10.1109/68.924013

Publication date:
2001

Document Version
Publisher's PDF, also known as Version of record

Ultrafast Gain Recovery and Modulation Limitations in Self-Assembled Quantum-Dot Devices

Tommy W. Berg, Svend Bischoff, Ingibjorg Magnusdottir, and Jesper Mørk

***Abstract*—Measurements of ultrafast gain recovery in self-assembled InAs quantum-dot (QD) amplifiers are explained by a comprehensive numerical model. The QD excited state carriers are found to act as a reservoir for the optically active ground state carriers resulting in an ultrafast gain recovery as long as the excited state is well populated. However, when pulses are injected into the device at high-repetition frequencies, the response of a QD amplifier is found to be limited by the wetting-layer dynamics.**

***Index Terms*—Gain recovery, quantum-dot amplifiers, ultrafast.**

I. Introduction

QUANTUM-DOT (QD) devices have been predicted to be superior to bulk or quantum-well (QW) devices in many respects. The realization of QD devices with ultralow threshold currents [1] indicates effective state filling, which opens for the potential of making ultrafast QD devices. The two key features necessary in such devices are high differential gain and fast carrier relaxation into the active states. High differential gain has proved to be present in many QD devices [2], [3] and, recently, ultrafast gain recovery on the scale of 100 fs has been demonstrated [4]. Despite these unique features, the maximum modulation frequency of present day QD lasers at room temperature is only 5–6 GHz [5], which is slower than bulk and QW devices. Here, we will analyze the gain recovery mechanisms of QD devices based on a comprehensive numerical model and, on this basis, give a possible explanation for the problems in realizing ultrafast QD devices.

II. Model

There are two general approaches to modeling of QD devices: rate equation models (REMs), which are a generalization of the approach used to model bulk/QW devices, and master equation models (MEMs) of the type suggested by Grundmann *et al.* [6]. The results presented here have all been obtained with a REM. However, all results have been verified by a corresponding MEM, giving nearly identical results in the regime explored in this letter. The REM used here will be described in the following,

The dots are assumed to contain two discrete energy levels: a nondegenerate ground state (GS) level and a doubly degenerate excited state (ES) level (not counting spin). The population of these two levels is described by separate carrier densities, N_G and N_E, which are normalized with respect to the total dot volume V_D. Dots are interconnected by the wetting layer (WL), described by the carrier density, N_W, which is normalized to the WL volume V_W. We assume that carriers are injected directly from the contacts into the WL and the barrier dynamics are thus ignored in the model.

The rate equations describing the change in carrier densities of the three energy levels are given as follows:

$$\frac{\partial N_W}{\partial t} = \frac{I}{eV_W} + \frac{N_E}{\tau_e^E}\frac{V_D}{V_W}f'_W - \frac{N_W}{\tau_c}f'_E - \frac{N_W}{\tau_{sp}}$$

$$\frac{\partial N_E}{\partial t} = \frac{N_W}{\tau_c}\frac{V_D}{V_W}f'_E + \frac{N_G}{\tau_e^G}f'_E - \frac{N_E}{\tau_e^E}f'_W - \frac{N_E}{\tau_0}f'_G - \frac{N_E}{\tau_{sp}}$$

$$\frac{\partial N_G}{\partial t} = \frac{N_E}{\tau_0}f'_G - \frac{N_G}{\tau_e^G}f'_E - \frac{N_G}{\tau_{sp}} - \frac{L}{V_D}g_G\frac{P_G}{\hbar\omega_G}.$$

Here, τ_e^E is the escape time of carriers from the ES level to the WL and $f'_{W,E,G} = 1 - f_{W,E,G}$ are the probabilities of finding an empty carrier state at the WL bandedge, the ES and GS levels, respectively (which are closely related to the carrier densities of the corresponding levels). τ_c is the capture time of carriers from the WL to the ES level, τ_{sp} is the spontaneous recombination time (assumed identical for all levels), τ_e^G is the excitation time of carriers from the GS level to the ES level, τ_0 is the intradot relaxation time, L is the length of the amplifier, and P_G is the intensity of the optical field interacting with the GS transition with photon energy $\hbar\omega_G$. The gain coefficient of the GS transition g_G is given as

$$g_G = \Gamma_D a_G(2N_G - \rho_G N_D)$$

with Γ_D being the confinement factor of the dots, a_G the linear gain coefficient of the GS level, ρ_G the degeneracy of the GS level without spin (equal to 1 in this case), and N_D is the number of dots divided by the volume of dots.

Both phonon- and Auger-assisted capture and relaxation are taken into account phenomenologically through the relation

$$\tau_i = \frac{1}{A_i + C_i N_W}, \qquad i = c, 0$$

where $1/A_C$ $(1/A_0)$ is the phonon-assisted capture (relaxation) time and $C_c(C_0)$ is the coefficient determining the rate of Auger-assisted capture (relaxation) by scattering with carriers in the WL.

Relaxation and excitation times are interconnected through a quasi-Fermi equilibrium condition, which means that the system will evolve toward a Fermi distribution if given sufficient time.

Manuscript received January 9, 2001; revised February 21, 2001.

The authors are with Research Center COM, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark (e-mail: twb@com.dtu.dk).

Publisher Item Identifier S 1041-1135(01)04546-3.

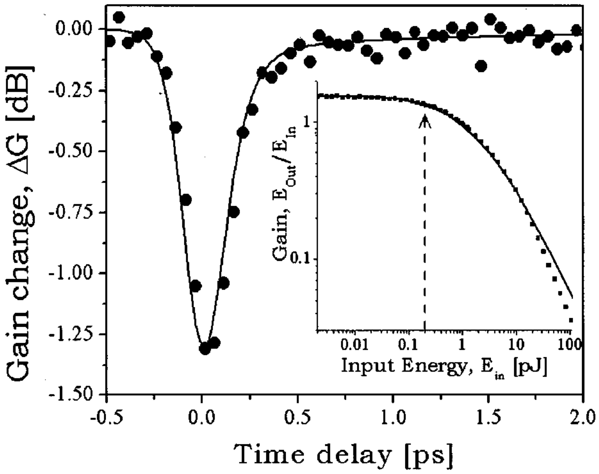

Fig. 1. Measured (dots) and calculated (solid line) pump probe response of the amplifier in the gain regime. The inset compares the measured (squares) and calculated (solid line) saturated single pulse gain as function of input pulse energy. The dashed arrow indicates the pump pulse energy used in the pump probe experiment. Experimental data are taken from Borri *et al.* [4].

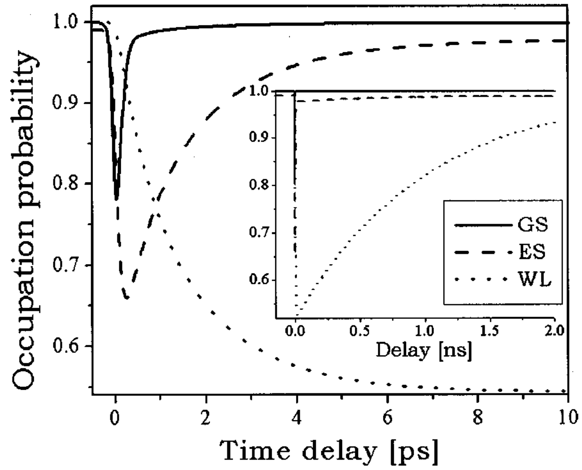

Fig. 2. Calculated evolution of occupation probability for the ground state (GS), excited state (ES), and wetting layer (WL) of the QD-amplifier, when a 150-fs pump pulse is injected at time delay zero. The insert shows the long-term changes.

The relations derived under the condition that the quasi-Fermi level of the system is far below the WL bandedge are

$$\tau_e^E = \tau_c \frac{2\rho_E N_D V_D \pi \hbar^2}{\mathrm{WL} m_e^* k_B T} \exp\left(\frac{E_W - E_E}{k_B T}\right)$$

and

$$\tau_e^G = \tau_0 \frac{\rho_G}{\rho_E} \exp\left(\frac{E_E - E_G}{k_B T}\right).$$

Here, W is the width of the active region, m_e^* the effective electronic mass, E_W the energy of the WL bandedge, $E_{E,G}$ the energies of the GS and ES levels, and ρ_E the degeneracy of the ES level (equal to 2 in this case).

Propagation of the optical field through the device is governed by a standard propagation equation, which includes a two-photon absorption (TPA) term.

The values used for the capture and relaxation coefficients are $A_c = 10^{12}\mathrm{s}^{-1}$, $C_c = 10^{-14}\mathrm{m}^3 \cdot \mathrm{s}^{-1}$, $A_0 = 10^{11}\mathrm{s}^{-1}$, and $C_0 = 7 \times 10^{-12}\mathrm{m}^3 \cdot \mathrm{s}^{-1}$, which results in a phonon dominated capture time on the order of 1 ps and an Auger-dominated intradot relaxation time around 100 fs for the WL carrier densities used here. The capture time and phonon-assisted relaxation times are in good agreement with values typically reported in the literature [7], [8]. The Auger-assisted relaxation is fast compared to most previous reports but agrees with the value found in [4]. The fast relaxation might be related to the existence of an overgrowth layer, which only enters the equations through the value of the above coefficients. The differential gain and the TPA coefficient have been fitted to the experimental data and the values found in this way are $a_G = 4.6 \times 10^{-18}\,\mathrm{m}^2$ and $\alpha_{\mathrm{TPA}} = 11 W^{-1} \cdot \mathrm{m}^{-1}$. All other parameter values are determined from the information supplied about the device [4], [9].

III. Results

Fig. 1 shows the experimental and numerical pump probe response in the saturated gain regime of a 475-μm-long InAs QD-amplifier (see [4] for device details) when a 150-fs pump pulse is amplified. The inset shows the saturated gain as function of pulse input energy. In both cases, good agreement between model and measurement is observed.

The gain is observed to recover nearly completely in less than 0.5 ps, which is significantly faster than observed in other active semiconductor devices.

The explanation for the fast gain recovery can be seen in Fig. 2, which shows the variations of the carrier densities of the three different levels during the amplification of the strong pump pulse. As carriers from the GS level are removed through stimulated emission, ES level carriers relax quickly to the GS level on a time-scale of the duration of the pulse. This fast relaxation is a result of two features: the large energy splitting between the dot levels, which ensures slow thermal excitation of carriers, and a high WL carrier density, resulting in fast Auger-assisted relaxation. The ES level thus acts as a nearby carrier reservoir for the GS level enabling ultrafast gain recovery. Since the process of carrier capture is slower than intradot relaxation, the ES level recovers on a longer time-scale of several picoseconds. Finally the WL is in the insert of Fig. 2 seen to recover on a nanosecond timescale. The rate of refilling of this upper level is essentially determined by the injection current and the spontaneous recombination rate of the WL.

The ultrafast gain recovery following a single pulse excitation could lead to the belief that the QD amplifier allows for ultrafast all-optical signal processing in the Tbit/s range. However, due to slow refilling of the WL level, this is not the case. Fig. 3 shows the gain dynamics when a train of short pulses is injected for two different repetition rates: 10 and 40 GHz. In both cases, the pulsewidth is 150 fs and the average signal input power is 10 mW, which means that the peak intensity of the 10-GHz signal is four times higher than the 40-GHz signal.

For the 40-GHz signal the gain is seen to recover almost completely after the first pulse, similar to the single pulse case shown in Fig. 1. However, after each of the following pulses the gain recovers progressively slower and, hence, reaches a smaller absolute value before the next pulse arrives, until only small deviations from transparency are observed. The evolving gain sat-

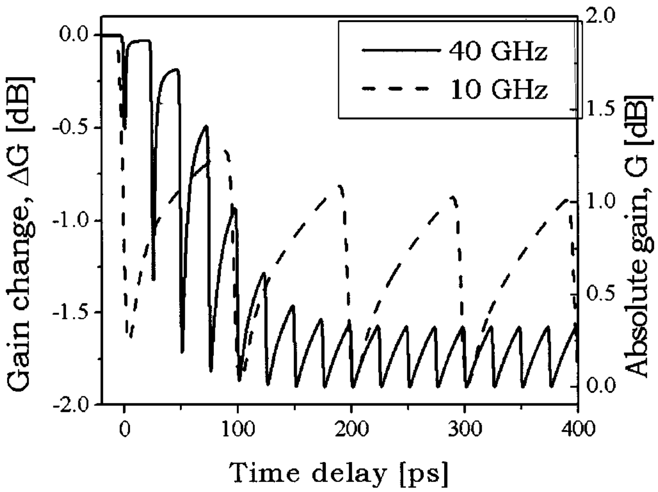

Fig. 3. Gain change under injection of a periodic train of short pulses with a repetition rate of 40 GHz (solid line) and 10 GHz (dotted line), under operating conditions identical to those used in Figs. 1 and 2. The right axis shows the corresponding absolute gain.

uration is a result of the decreasing WL carrier density, which leads to a reduced Auger relaxation rate and to a depletion of the ES level, which initially acted as reservoir for the GS level. This leads to a significant reduction in the relaxation rate and as a result the gain is not able to recover after each pulse at this repetition rate.

For the 10-GHz signal an initial gain decrease is also observed, but the system quickly stabilizes and the gain recovers repeatedly to half of the initial value. This partial recovery indicates that this repetition rate is close to the actual speed limit of the device, where the recovery is not dependent on the reservoir effect of the ES level.

The approximate limit of 10 GHz seen in Fig. 3 is comparable to the maximum bandwidths of 5–6 GHz reported so far for directly modulated QD lasers [5]. The slow gain recovery, illustrated above, is expected to limit both lasers and amplifiers. A similar conclusion has been reached by Deppe *et al.* [9], who have pointed out that the large density of states in the WL causes a strong temperature dependence of the modulation response, which limits the bandwidth of QD lasers at room temperature. It is thus clear that in order to improve QD device operating speed it is necessary to improve the dynamics of the upper levels or completely circumvent the WL. One improvement in this respect might be a tailoring of the overgrowth layer. An overgrowth layer has been shown to increase the capture efficiency [10]. Further out in the supply chain of carriers to the active region, there must also be a finite capture time of carriers from the barriers into the WL. This process can be expected to resemble the capture process in QW devices and, therefore, gives rise to limitations similar to those seen in this type of device. However, further work is needed to understand the interplay between WL and outer barrier reservoirs in relation to the refilling of the WL.

In conclusion, ultrafast gain recovery in QD amplifiers is possible due to excited states acting as reservoir for the ground state-level. It is thus not the recovery time of the ground state, but rather the recovery times of the excited states and the wetting layer, which limit the performance. The reduction of the recovery time of these upper levels is a key point for increasing the speed of QD devices.

ACKNOWLEDGMENT

The authors gratefully acknowledge P. Borri *et al.* of [4] for supplying the experimental data shown in Fig. 1.

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