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Impact of carrier-carrier scattering and carrier heating on pulse train dynamics of quantum dot semiconductor optical amplifiers

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We investigate the impact of carrier-carrier scattering on the gain recovery dynamics of a quantum dot (QD) semiconductor optical amplifier. Simulations, based on semiconductor Bloch equations with microscopically calculated Coulomb scattering rates between the carrier reservoir and the QDs, show a very good agreement with experimentally obtained pump-probe dynamics over a range of injection currents. With the microscopically obtained scattering rates at hand, we can conclude that fast cascading relaxation processes between the two-dimensional carrier reservoir and the QDs in combination with carrier heating enhancing the scattering efficiency drives the ultrafast gain recovery observed in QD based semiconductor devices. © 2011 American Institute of Physics. [doi:10.1063/1.3643048]

Semiconductor devices with self-assembled quantum dots (QDs) as the gain source are experiencing an ever growing interest due to the nanoscale size of the QDs and the associated discrete nature of the energy levels.^{1–3} Nanolasers, single photon sources, or ultralow threshold devices can be realized using QDs.^{4,5} In this work, we focus on the aspect of ultrafast gain recovery associated with efficient carrier scattering mechanisms between the QDs and the surrounding carrier reservoir (QW).^{6–10} We have measured the gain recovery of a *InGaAs/GaAs* quantum dot based semiconductor optical amplifier (SOA) after the amplification of different short pulse trains (one, two, and four pulses). By incorporating carrier heating effects into the model, we achieve an excellent agreement with ultrafast pump-probe measurements. Although attempts have been made to include carrier heating in QD SOA models, it remains a controversial issue.¹¹

The model chosen to simulate the pump-probe dynamics is adapted from Ref. 12. It consists of coupled coherent optical Bloch equations for the quantum dot interband polarizations and electron and hole occupation probabilities. The QD carriers are coupled to a two-dimensional (2D) QW by means of Auger scattering processes, which are calculated on a microscopic level via density matrix theory. In the following, we denote by the superscript j the j th subgroup of QDs of the inhomogeneously broadened ensemble with 2D density N^j and frequency detuning $\delta\omega_m^j$ with respect to the input light field. The full width at half maximum (FWHM) of the energy broadening distribution is taken to be 20 meV. The QD ground state (GS) and the first excited state (ES) are discriminated by a level index m .¹² The dynamical equations for the QD interband polarizations p_m^j , describing the probability of an optical transition between the respective electron and hole levels, the QD carrier occupation probabilities $f_{e/h,m}^j$ of electrons (e) and holes (h), respectively, and the 2D carrier densities in the reservoir $w_{e/h}$ in slowly varying envelope and

rotating wave approximation are given by the following five equations

$$\frac{\partial p_m^j}{\partial t} = -i\delta\omega_m^j p_m^j - i\frac{\Omega}{2}(f_{e,m}^j + f_{h,m}^j - 1) - \frac{1}{T_2} p_m^j, \quad (1)$$

$$\frac{\partial f_{e/h,m}^j}{\partial t} = -\text{Im}[\Omega p_m^{j*}] - R_{sp} + \left. \frac{\partial f_{e/h,m}^j}{\partial t} \right|_{col}, \quad (2)$$

$$\frac{\partial w_{e/h}}{\partial t} = \frac{j(t)}{e_0} - \tilde{R}_{sp} - 2 \sum_{m,j} N^j \left. \frac{\partial f_{e/h,m}^j}{\partial t} \right|_{col}, \quad (3)$$

where the subscripts e/h denote two separate equations each in Eqs. (2) and (3). Scattering induced coherence loss is accounted for by a dephasing time T_2 . The electric current density injected into the QW is given by $j(t)$. Hereby, we neglect carrier transport between the bulk- and 2D carrier reservoir. The intrinsic Rabi frequency of the QD transitions with associated dipole moment $\mu = 0.6e_0 \text{ nm}$, where e_0 is the elementary charge, enters as $\Omega(t) = \frac{\mu}{\hbar} E(t)$ in Eq. (2). The complex slowly varying electric field amplitude $E(t)$ is taken to be a Gaussian signal with a FWHM of 150 fs in resonance with the QD ground state transition. Losses due to spontaneous emission in the QDs and the QW are given by R_{sp} and $\tilde{R}_{sp}$, respectively.¹² An important part of the carrier dynamics is given by the carrier scattering contributions $(\partial/\partial t)_{e/h,m}^j|_{col}$ leading to a redistribution of carriers within the QW-QD system. They are mainly made up of carrier-carrier and carrier-phonon collisions. Under high excitation conditions, i.e. in our case strong electrical pumping, carrier-carrier collisions are typically more efficient than carrier-phonon scattering. Therefore, we neglect phonon scattering contributions between QW and QDs. The carrier-carrier scattering rates are calculated in a perturbation approach up to second order in the screened Coulomb potential within Markov approximation. It involves the evaluation of

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screened Coulomb matrix elements with QD and QW wave functions of the single particle states. The total rate is obtained by summation over all possible transitions between QD and QW states. The QW states are described by quasi-Fermi distributions. This implies that equilibration processes within the QW, mainly carrier-phonon collisions, are fast compared to all processes driving the system away from quasi-equilibrium, e.g., current injection and Coulomb scattering between QW and QD states. The calculation of Coulomb scattering contributions has been described in detail elsewhere.^{12,13} As a new feature, here, we take into account plasma heating effects as observed in Ref. 14, and as was already successfully implemented in a QD laser model to describe its modulation characteristics.¹⁵ Injection of carriers into high energy states of the QW leads to an increase of the carrier plasma temperature and via carrier-phonon scattering processes also to an increase of the lattice temperature. Coupling to an external heat bath (the environment) counteracts carrier heating. The overall effect of plasma heating appears in the dependence of the device temperature on the electric pumping¹⁴ and in temperature dependent scattering rates. The population of the QW follows a quasi-Fermi distribution that varies with the carrier plasma temperature and therefore influences the Coulomb scattering rates. The considered Auger rates in dependence of the QW density and temperature are shown in Fig. 1. For electrons [holes], panels (a) and (b) [(e) and (f)] show Coulomb in-scattering rates for direct capture processes of carriers into the QD ground ($S_{e/h,GS}^{in,cap}$) and first excited state ($S_{e/h,ES}^{in,cap}$) as schematically shown in the inset (i) of Fig. 1, respectively, while panels (c) and (d) [(g) and (h)] show relaxation rates involving a redistribution of carriers between the intradot QD ground and excited state levels ($S_{e/h}^{in,rel}$, $S_{e/h}^{in,rel'}$) as sketched in the inset (ii) of Fig. 1.¹²

FIG. 1. (Color online) Density plots of the calculated Coulomb scattering rates in dependence of the QW electron density w_e and the plasma temperature T for fixed ratio $w_h/w_e = 1.5$. The assumed temperature characteristic of the device is shown by the white curves. Black dots mark the initial steady states used in the pump-probe simulations. [(a) and (b)]: Electron in-scattering rates for direct capture processes to the QD GS and ES, respectively. [(c) and (d)]: Electron relaxation rates for processes involving one intradot transition accompanied by a carrier transition within the QW or two QD-QW transitions, respectively. [(e) and (f)]: Hole in-scattering rates for direct capture processes to the QD GS and ES, respectively. [(g) and (h)]: Same as (c) and (d) for holes. The color code is in units of ps^{-1} . The insets show schematically (i) direct electron capture processes, (ii) electron relaxation processes. Parameters see Table I.

FIG. 2. (Color online) (a): Measured (exp) and simulated (sim) gain recovery dynamics for a single injected pump pulse and injection currents of $j = 8j_0$ (red “o” symbols and solid curve), $j = 11j_0$ (green “x” symbols and dashed line), $j = 15j_0$ (blue “Δ” symbols and dash-dotted curve) (b): Gain recovery dynamics for two injected pump pulses with a spacing of $\Delta t = 1$ ps ($T = 325$ K and $T = 401$ K correspond to the initial temperatures). (c): Gain recovery dynamics for four injected pump pulses with a spacing of $\Delta t = 1$ ps.

and (h)] show relaxation rates involving a redistribution of carriers between the intradot QD ground and excited state levels ($S_{e/h}^{in,rel}$, $S_{e/h}^{in,rel'}$) as sketched in the inset (ii) of Fig. 1.¹² The temperature characteristic of the device along which the temperature varies in the dynamic simulation is modeled as linearly depending on the QW electron density in the range of interest. It is given by the white curves in Fig. 1. The initial temperature values for the different injection currents are marked by the black dots in Fig. 1. This is in good agreement with measurements performed in Ref. 14, where the device temperature was extracted from a calibrated measurement of the displacement of the ripple modes in the SOA’s cavity. In Fig. 1, an increased scattering efficiency for higher plasma temperatures is visible. For the given energetic configuration, the overall relaxation rates are much larger than the direct capture rates. Out-scattering is related to in-scattering via detailed balance¹⁶ and is not shown in the figure. Both in- and out-scattering rates enter as Boltzmann terms in the collision contributions $(\partial/\partial t)_{e/h,m}^j|_{col}$ appearing in Eqs. (2) and (3).¹² The investigated device is a $4\mu m$ wide and 1 mm long ridge waveguide structure, with $InAs$ QDs embedded in a $InGaAs$ QW surrounded by a $GaAs$ cladding layer. It has tilted facets to avoid backreflections with additional antireflection coating. The QD GS energy levels are set to 74 meV

FIG. 3. (Color online) (a): Calculated average electron populations in the QD ground state (red solid curve) and excited state (red dashed curve) and QW (black dashed curve) vs time for an injection current density $j = 8j_0$ in the presence of the pump pulse only. (b) Same as (a) for hole populations.

TABLE I. Numerical parameters used in the simulation other than in Ref. 12.

Symbol	Value	Symbol	Value
$\Delta E_{e,GS}^{QD}$	74 meV	$\Delta E_{e,ES}^{QD}$	24 meV
$\Delta E_{h,GS}^{QD}$	40 meV	$\Delta E_{h,ES}^{QD}$	20 meV
Δ_e	50 meV	Δ_h	20 meV
T_2	30 fs	$\Theta = \int \Omega dt$	1.18π
j_0	40 Acm ⁻²	N^{QD}	10^{11} cm ⁻²
m_e	0.067 m_0	m_h	0.45 m_0

below the QW band edge for electrons and 40 meV for holes. The ES electron and hole energy levels are 24 meV and 20 meV below the band edge, respectively.

The measured gain recovery dynamics together with the simulated curves are shown in Fig. 2 for a single pulse pump-probe setup (a), a dual pulse setup (b), and a setup with four pump pulses (c). The pump-pulse spacing is chosen as $\Delta t = 1$ ps in accordance with the experiments and the arrival time of the first pump signal is at $\tau = 0$. The experimental data are shown for injection currents of 80 mA, 110 mA, and 150 mA, whereas the simulations are depicted for injection current densities $j = 8 j_0$, $11 j_0$, and $15 j_0$ given in multiples of the transparency current density j_0 , which corresponds approximately to a transparency current of 10 mA enabling a direct quantitative comparison. The simulated gain recovery dynamics in Fig. 2 is in excellent agreement with the measured data for all pump-probe setups (one, two, and four pulses). Both in the ultrafast gain recovery stage ($\tau \approx T_2$), where the coherent dynamics of the polarization is essential and in the fast recovery stage, where τ is on the order of the carrier lifetime given by the Coulomb scattering between QW and QDs ($\tau \geq 1$ ps), the simulated curves match the measured data very well.

The carrier dynamics obtained from the simulation in the presence of the pump pulse only is shown in Fig. 3 for an injection current density of $j = 8 j_0$. The input pulse is centered around $t = 0$. A clear signature of a strong cascading relaxation process is visible, where the QD ground state is quickly refilled by carriers from the excited state, which in

turn shows a carrier depletion setting in with the arrival of the pulse, and is slowly refilled from the QW.

In conclusion, we have shown that Coulomb scattering in combination with carrier heating accurately describes the gain recovery dynamics of ultrashort pulse trains in electrically driven QD SOAs as observed in pump-probe measurements. By including ground and excited state Coulomb processes we capture the essential scattering mechanisms that enable the ultrafast gain recovery in QD-QW systems under strong electrical injection. We demonstrate that carrier heating is a key factor in enhancing the scattering efficiency, which in turn leads to faster gain recovery and improved device performance.

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