The Role of Decoupled Electron and Hole Dynamics in the Turn-on Behavior of Quantum-Dot Lasers

Kathy Lüdge, Ermin Malić, and Eckehard Schöll
Institut für Theoretische Physik, Technische Universität Berlin, Germany

Halbleiter-Nanophotonik SFB 787

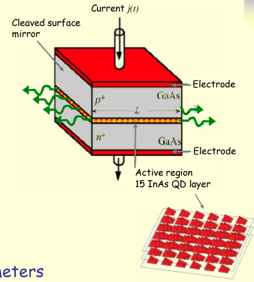
Introduction

Quantum-dot (QD) injection lasers promise low threshold current, low bit-error rate and large temperature stability for optoelectronic application.

The **nonlinear dynamic response** of QD lasers can be quantitatively understood by including the strongly nonlinear character of electron-electron scattering processes. We demonstrate the importance of the **mixed electron-hole Auger capture processes** that depend on both the electron and the hole density in the wetting layer (WL). Moreover a **decoupling of hole and electron dynamics** in the dots leads to the experimentally found small cut-off frequency of these lasers.

Model: -Microscopic approach for calculating carrier-carrier scattering rates (Auger transitions)
-Rate equations (5 variables) for directly modulated QD laser

Goal: Simulation of the turn-on behavior of the QD laser



Rate Equation Model

$$\dot w_e = j(t)\frac{\eta}{e_0} - S_e^{in}\frac{N^{WL}}{N^{QD}}(N^{QD}-n_e) + S_e^{out}\frac{N^{WL}}{N^{QD}}n_e - \frac{W}{N^{WL}}w_e w_h$$

$$\dot n_e = S_e^{in}(N^{QD}-n_e) - S_e^{out}n_e - WA(n_e+n_h-N_{QD})n_{ph} - \frac{W}{N^{QD}}n_e n_h$$

$$\dot n_{ph} = -2\kappa n_{ph} + \Gamma WA(n_e+n_h-N_{QD})n_{ph} + \beta\frac{W}{N^{QD}}n_e n_h$$

$$\dot n_h = S_h^{in}(N^{QD}-n_h) - S_h^{out}n_h - WA(n_e+n_h-N_{QD})n_{ph} - \frac{W}{N^{QD}}n_e n_h$$

$$\dot w_h = j(t)\frac{\eta}{e_0} - S_h^{in}\frac{N^{WL}}{N^{QD}}(N^{QD}-n_h) + S_h^{out}\frac{N^{WL}}{N^{QD}}n_h - \frac{W}{N^{WL}}w_e w_h$$

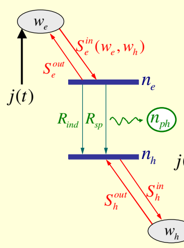
- Assumption of fast intradot relaxation → only lowest energy level in QD
- Continuous 2D WL states
- Pump current injected into wetting layer
- Boltzmann equation for occupation probability **ρ** in the dots

$$\dot\rho_h = S_h^{in}(1-\rho_h) - S_h^{out}\rho_h, \quad n_h = N^{QD}\rho_h$$
$$\dot\rho_e = S_e^{in}(1-\rho_e) - S_e^{out}\rho_e, \quad n_e = N^{QD}\rho_e$$

Parameters

- W : Einstein coefficient (1.3ns^{-1})
- N^{WL} : density of states in WL ($2\cdot10^{13}$cm^{-2})
- N^{QD} : QD density ($1\cdot10^{10}$cm^{-2})
- Γ : optical confinement factor (0.0011)
- β : spontaneous emission coefficient ($5\cdot10^{-6}$)
- κ : total cavity loss (0.12 ps^{-1})
- A : lateral ridge dimension (4μm · 1mm)

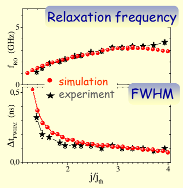
Band structure

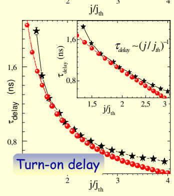


- n_{ph} : photon density
- n_e, n_h : carrier density in QDs
- w_e, w_h : carrier density in the WL
- $S_{e/h}^{in/out}$: Auger scattering rates
- j : pump current
- η : injection efficiency

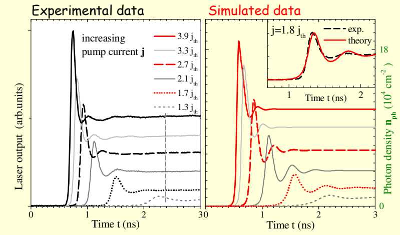
Simulation vs. Experiment

➧ Simulations of laser turn-on dynamics show strongly damped relaxation oscillation in **excellent agreement** with experiments at TU Berlin (AG Bimberg)

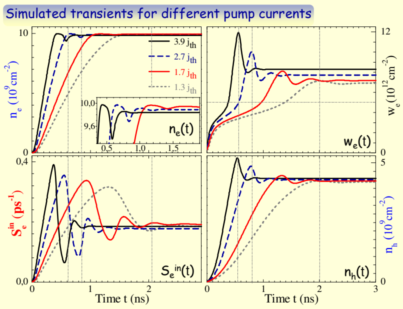




Turn-on dynamics

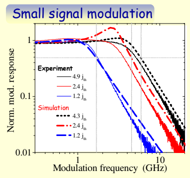


Simulated transients for different pump currents

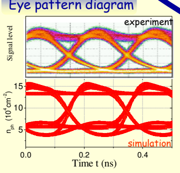


- Simulated transients show coupled dynamics for w_e and w_h and **decoupled** behavior for n_e and n_h.
- g_c self consistently determined for each pump current j (artifacts evolve in transients if g_c is too large).

Small signal modulation



Eye pattern diagram



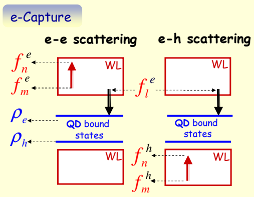
5Gbits/s

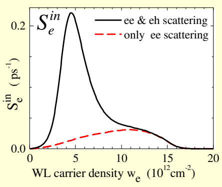
- **Symmetric shape** of eye pattern due to strong damping

- Pump current j given in units of threshold current j_{th} determined from steady state input-output characteristics.

Microscopically Calculated Scattering Rates (Auger Transitions)

e-Capture





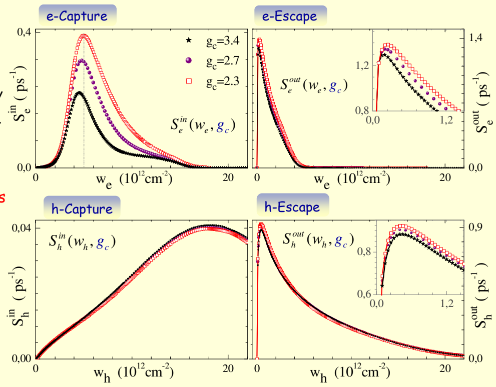
- Auger transition between localized QD and continuous WL states (energy and momentum conservation)
- Consider also electron-hole scattering → Scattering rates $S_{e/h}^{in/out}$ depend on w_e and w_h.
- Electron-hole scattering very effective for small carrier densities

➧ Electron-hole scattering is important !

$$S_e^{in}(w_e,w_h) = \frac{2\pi}{\hbar}\sum_{lmne_2} M_{enlm}(2M^*_{enlm} - \delta_{e,e_2}M^*_{enml})f_l^e f_m^{e_2}(1-f_n^{e_2})\delta(E^e+E_n^{e_2}-E_l^e-E_m^{e_2})$$

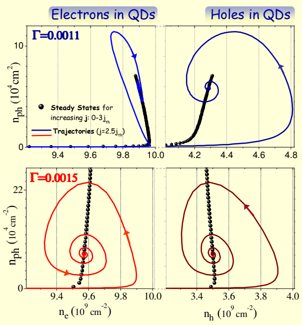
- Scattering rates are determined by the matrix elements M_{enlm} and the occupation probabilities f_k of the involved WL states.
- Simulations of S_e (S_h) are performed for continuously increasing w_e (w_h) and fixed ratio between w_e and w_h.
  - we introduce $g_c = \frac{w_h}{w_e}$

➧ Different g_c changes amplitude of scattering rates.



- **In-scattering:** at high densities rate decreases because of missing empty states for Auger electron
- **Out-scattering:** first increases due to more scattering partners, later exponential decrease due to Pauli blocking
- **Holes** have larger effective mass → filling is slower

Dynamics in Phase Space - Dependence on Confinement Parameter Γ

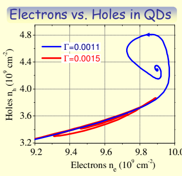


- Threshold carrier density in QDs:

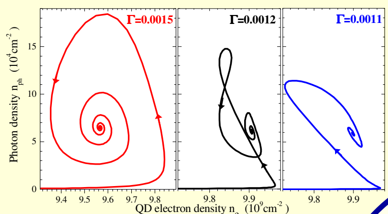
$$n_e + n_h\big|_{th} = \frac{2\kappa}{\Gamma WA} + N^{QD} = const$$

- QDs negatively charged
- Nearly all states in QDs are occupied $n_e \approx N^{QD}$

Electrons vs. Holes in QDs



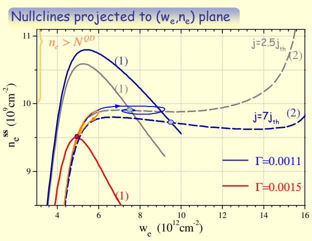
- Small Γ=0.0011
  → Separate dynamics of elec. and holes
- Increased Γ=0.0015
  → Coupled dynamics of electrons and holes
  → Faster relaxation osc. (like QW Laser)



- Γ changes with number of QD layers, QD density and layer thickness

- Γ=0.0012 (transition regime)
  → Clef-like shape; change from clockwise to anticlockwise rotation in (n_e,n_{ph}) plane

Nullclines projected to (w_e,n_e) plane



$$(1)\quad n_e^{ss}(w_e,g_c(j)) = \frac{\frac{2\kappa}{\Gamma WA}\left(S_h^{in}+S_h^{out}\right) + N^{QD}\left(S_e^{in}+S_h^{out}\right)}{S_e^{in}+S_e^{out}+S_h^{in}+S_h^{out}}$$

$$(2)\quad n_e^{ss}(w_e,g_c(j),j) = \frac{N^{QD}}{N^{WL}\left(S_e^{in}+S_e^{out}\right)}\left(S_e^{in}N^{WL} + \frac{W}{N^{WL}}g_c w_e^2 - \frac{\eta j}{e}\right)$$

damped regime : $n^{ss}{}_e(j) \approx N^{QD} - j\frac{N^{QD}}{eN^{WL}}\left(S_e^{in}+S_e^{out}\right)^{-1}$

oscillatory regime : $n^{ss}{}_e(j) \approx const.$

- Steady state values n_e^{ss} obtained from $\dot n_e = \dot n_h = \dot n_{ph} = \dot w_e = 0$
- Eq. (2) depends on Γ only in the damped regime (small Γ).
- Trajectories confined to the region $n_e < N^{QD}$

➧ Confinement factor Γ allows switching between two dynamic regimes.

Summary

We are able to **explain experimental data** of the dynamic response over a wide range of different pump currents. The strongly damped relaxation oscillations as well as delay time and relaxation frequency of the QD laser are nicely reproduced by the simulations. The nonlinearity of the scattering rates and the **incorporation of separate dynamics for holes and electrons** in the device are crucial in order to explain the dynamics of a QD laser. Even by neglecting effects like electron-phonon scattering, inhomogeneous broadening, and intradot relaxation processes, an excellent agreement with experiments could be met.

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References

K. Lüdge et al. Phys. Rev. B **78**, 035316 (2008)
E. Malić et al. IEEE J.Sel.Top. QE **13**, 1242 (2007)
M. Kuntz et al. Electron. Lett. **41**, 244 (2005)