Ultrafast Carrier Dynamics in p-doped InGaAs Quantum Dot Amplifiers

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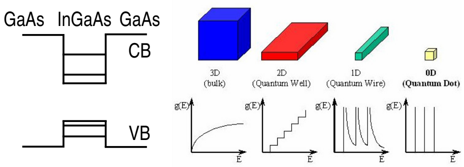
Introduction

Semiconductor quantum dot (QD) lasers and amplifiers are promising devices for optoelectronics due to a number of predicted superior performances of zero-dimensional systems. InGaAs QDs are among the most widely investigated systems in literature. These QDs can have defect free interfaces, strong confinement energies as well as room temperature emission in the 1.3-1.55μm wavelength range, appealing for optical telecommunication technology.

We have measured the ultrafast carrier dynamics of the QD ground state transition in p-doped electrically-pumped InGaAs QD optical amplifiers emitting near 1.3mm at room temperature. Three samples were investigated being respectively undoped, medium doped (about 8 holes per dot) and heavily doped (about 15 holes per dot).

What is a QD device?

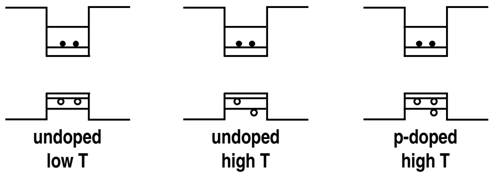
A QD is a drop of semiconductor material with nanometric size embedded in a wider energy gap matrix. The energy level structure is atom-like giving a peaked density of states.



The zero dimension properties of QDs can be exploited in laser devices for lower threshold current and superior thermal stability.

In the InGaAs/GaAs QDs the hole level energy spacing (<20meV) is smaller than KT at room temperature. Holes are thermally excited to higher levels reducing the population inversion and consequently the maximum gain available.

A possible solution to overcome this problem is the introduction of additional holes by doping the dots.

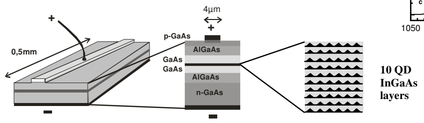


Samples: InAs/GaAs/AlGaAs Quantum Dot Optical Amplifiers

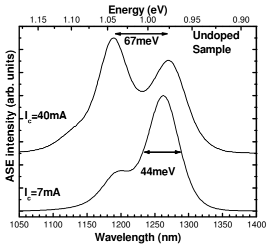
Semiconductor Optical Amplifiers (SOA)

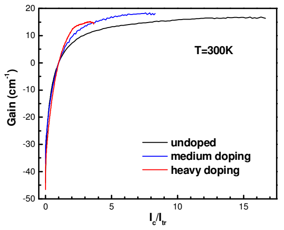
- MBE-grown, emitting at 1.3μm
- 3 different p-doping levels (by C in the spacer layers), otherwise identical:

- **U**ndoped
- **M**edium doped (8 acceptors per dot estimated)
- **H**eavily doped (15 acceptors per dot estimated)



Sample Characterization

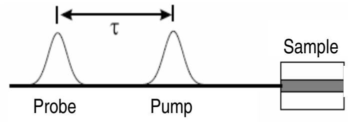




Transparency current increasing with doping:

Undoped I_{tr}=2.40mA, **Medium doped** I_{tr}=4.81mA, **Heavily doped** I_{tr}=19.1mA

Experiment: Pump-probe dynamics resonant to exciton ground state



The gain change is deduced from the transmission change as calculated by $\Delta G(\mathrm{dB}) = 20\log\left(1+\frac{\Delta T}{T_0}\right)$ where $\Delta T = T - T_0$ and $T(T_0)$ is the probe transmission with (without) pump.

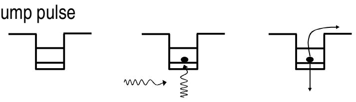
Electron-hole density dynamics after pump pulse due to

- Carrier-carrier scattering
- Carrier-Phonon scattering
- Radiative recombination and current injection

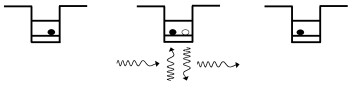
Carrier redistribution between

- QD ground and excited states
- QD and wetting layer

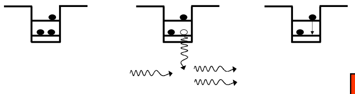
- **Absorption regime:** electron hole pairs are created by the optical pump pulse

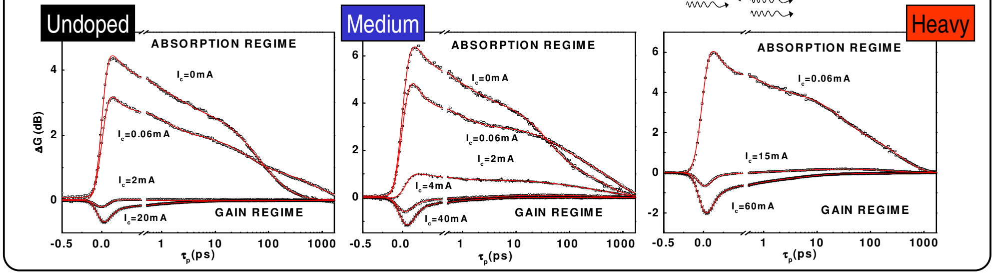


- **Transparency**: zero net change of electron-hole pairs by pump Pulse.The dynamics are dominated by instantaneous processes.



- **Gain regime:** electron hole pairs are removed by the optical pump pulse.

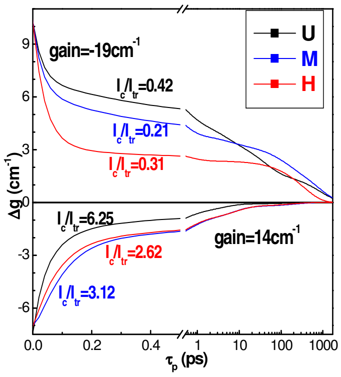


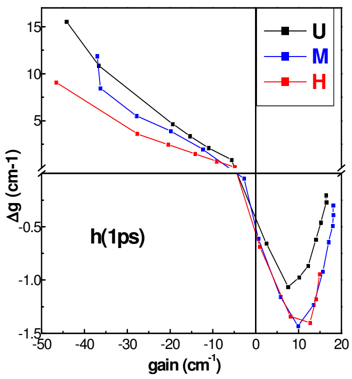


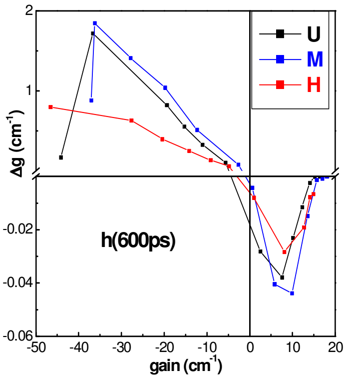
Analysis

Fitted with $\int I(t)h(t-t')dt'$: convolution of **pulse intensity autocorrelation I(t)** with the **multi-exponential response function h(t):**

$$h(t) = a_0\delta(t) + \sum_{i=1}^{4} a_i \exp\left(-\frac{t}{T_i}\right)\Theta(t)$$







- In the **absorption regime** the doping results in a faster recovery : stronger carrier-carrier scattering by **doping related hole density**
- In the **gain regime** the recovery is faster in the undoped sample : an **higher electron density in the excited states** for the undoped sample (as shown from the Amplified Spontaneous Emission) results in a faster redistribution of the carriers and a faster gain recovery. The highest carrier population for the undoped sample is shown from ASE and gain measurements.

Conclusion

From the analysis of the measurements we distinguish four different time constants characterizing the carriers dynamics (in the 0.08-0.4ps, 0.8-4ps, 10-100ps and 0.1-1ns range, respectively) and we infer their relative weights as a function of electrical injection. Comparison between the samples indicates that the main effect of p-doping is a fastening of the carrier dynamics in the absorption regime, while for electrical injection above transparency the ultrafast gain recovery dynamics of the undoped sample is faster than in the p-doped samples.

In the absorption regime the additional holes of the doped samples lead to stronger carrier-carrier scattering and consequently to a fast absorption recovery. Instead, surprisingly, in the gain regime the higher electron population of the excited states of the undoped sample leads to a faster gain recovery for the undoped sample compared to the doped ones.