

# Observation of trapping and release of carriers in InGaAs/GaAs quantum dots by ultrafast THz spectroscopy

**Porte, Henrik; Jepsen, Peter Uhd; Daghestani, Nart; Rafailov, Edik; Turchinovich, Dmitry**

*Published in:*
IEEE LEOS Annual Meeting Conference Proceedings, 2009. LEOS '09.

*Link to article, DOI:*
10.1109/LEOS.2009.5343415

*Publication date:*
2009

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

# Observation of Trapping and Release of Carriers in InGaAs/GaAs Quantum Dots by Ultrafast THz Spectroscopy

Henrik Porte*, Peter Uhd Jepsen*, Nart Daghestani†, Edik Rafailov†, and Dmitry Turchinovich*
*DTU Fotonik - Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
Email: dmtu@fotonik.dtu.dk
†School of Engineering, Physics and Mathematics, University of Dundee, Dundee DD1 4HN, UK

***Abstract*—Depending on the photoexcitation wavelength, we either observe the trapping of the free carriers into quantum dots, or release of carriers from quantum dot ground state into conducting states of the quantum dot sample.**

## I. Introduction

Ultrafast carrier dynamics processes in semiconductor quantum dots (QDs), such as trapping and release of carriers, is important for operation of many optoelectronic devices such as QD lasers, QD infrared photodetectors (QDIPs), and QD semiconductor saturable absorber mirrors (QD SESAMs). In order to observe these processes, we employed an optical pump - THz probe technique [1]. Tunable optical pump pulses were used to excite the carriers either into the conducting barriers, or resonantly into the insulating QD ground state (GS). The THz probe pulses are sensitive to the presence of the free carriers, but are not attenuated by the carriers localized in the QDs. Thus, by using an optical pump - THz probe technique we were able to monitor the population dynamics of the conducting states (CS) of the QD sample after photoexcitation (see Fig. 1(a)).

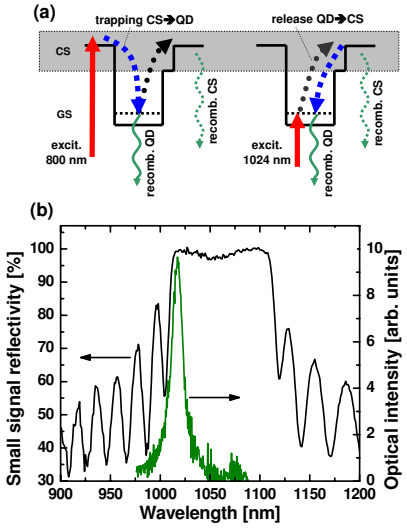


Fig. 1. a) Carrier dynamics processes in photoexcited QDs. CS - conducting state. GS - QD ground state. (b) Small signal reflectivity and room temperature optical emission spectra at 800 nm excitation of the studied QD SESAM.

## II. Sample, Experimental Results, and Discussion

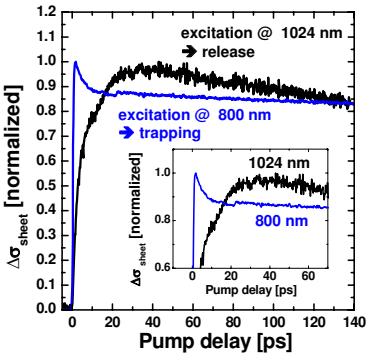


Fig. 2. Normalized $\Delta\sigma_{sheet}$ traces for QD GS and barrier excitation with the pump wavelength and fluence of 1024 nm and 22.8 $\mu$J/cm$^2$, and 800 nm and 1.18 $\mu$J/cm$^2$, respectively. Inset: zoomed-in traces.

As a sample we used a QD SESAM, grown by molecular beam epitaxy (MBE). It had 15 layers of $In_{0.5}Ga_{0.5}As$/GaAs QDs separated by GaAs spacers, grown on top of the $Al_{0.9}Ga_{0.1}As$/GaAs Bragg reflector. The total thickness of QD and spacer region was 611 nm. The sample was grown on a 0.5-mm thick semi-insulating GaAs substrate. The presence of a Bragg reflector in the sample was important for our experiment, since it was blocking the propagation of the pump light at resonant QD GS excitation into the GaAs substrate, thus preventing the generation of free carriers there by two-photon absorption mechanism. The small-signal reflectivity spectrum of the studied QD SESAM, as well as the room-temperature optical emission spectrum at 800-nm excitation, indicating the energetic position of the QD GS, are shown in Fig. 1(b).

An output of a regenerative Ti:Sapphire femtosecond amplifier, operating at a repetition rate of 1 kHz, and generating 45 fs pulses at 800 nm central wavelength, was split into three beans. One beam was used as a pump pulse: either directly, for excitation of the barrier states of the QDs at 800 nm; or after frequency conversion in an optical parametric amplifier (OPA) to 1024 nm, for resonant excitation of the QD GS. Two other beams were used to drive the standard nonlinear crystal – based THz time-domain spectrometer, with a sample

978-1-4244-3681-1/09/$25.00 ©2009 IEEE

positioned at its focal point [1]. The THz probe pulses were approximately 300-fs long, and had a useful spectrum of 0.5-2.5 THz. All our experiments were performed at room temperature.

As discussed above, the THz probe pulses are only sensitive to the population of the CS of the sample, but not to the population of the QDs. Both optical pump and THz probe pulses were normally incident onto a QD sample. Thus, the in-plane conductivity of the sample was probed with THz pulses. The relative transmission of the probe THz pulse can be quantified and converted into a photoinduced sheet conductivity $\Delta\sigma_{sheet}$ [2]. The typical results of the photoconductivity dynamics of the sample depending on the excitation wavelength are shown in Fig. 2. In case of barrier excitation at 800 nm, an instantaneous rise of photoconductivity due to direct injection of the free carriers, is followed by a very fast decay, associated to the trapping of these carriers into the QDs, and a much slower component caused by the conductivity in Type-II Bragg reflector, accessible to the pump light at this wavelength. If the QDs were resonantly excited in to the GS at 1024 nm, the maximum in the photoconductivity is reached only approximately 35 ps after the photoexcitation. We attribute this onset of the population of the CS to the release of the carriers from the QD GS to higher-energy CS, most likely driven by a large difference of densities of states between the QD GS and CS.

The maxima of $\Delta\sigma_{sheet}$ dynamics for 800 nm (1024 nm) excitation show linear (sub-linear) dependency on the pump fluence, as shown in Fig. 3, precisely as expected from a one-photon photoexcitation process. The saturation of maximum $\Delta\sigma_{sheet}$ for 1024 nm pump revealed a saturation fluence value of $F_s = 40$ $\mu$J/cm$^2$ [3], in reasonable agreement with the all-optical measurement on similar SESAMs [4].

The $\Delta\sigma_{sheet}$ dynamics for 1024 nm resonant QD GS excitation does not change significantly with increase in pump fluence. However, in the case of barrier excitation at 800 nm, we observed a slow-down of a fast decay component of $\Delta\sigma_{sheet}$ dynamics, associated with trapping of the carriers into QDs. We attribute this slowing down to filling up of the QD (trap) states with growth in excitation fluence [5], [6], [7]. In order to quantitatively estimate the trapping time, we have measured the 10% decay time constant, which shows near-linear growth with 800 nm excitation fluence (see Fig. 4).

## III. Conclusion

Using optical pump - THz probe technique, we were able to demonstrate the difference in ultrafast conductivity dynamics of a QD sample, depending on what state is optically excited: the QD GS or the barrier states. The observed dynamics can be explained by the dominating carrier release or carrier trapping processes in the QDs, respectively.


## Acknowledgment

We would like to thank Danish Advanced Technology Foundation (HTF) and EU FP7 Programme (FAST-DOT) grant 224338 for financial support.


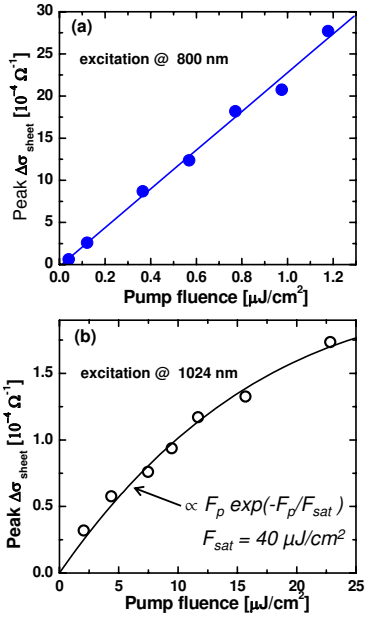


Fig. 3. Maximum of $\Delta\sigma_{sheet}$ traces as a function of pump fluence for (a) barrier excitation at 800 nm. Solid line: linear fit; and (b) resonant QD GS excitation at 1024 nm. Solid line: fit to the saturable absorption function with saturation fluence $F_s = 40$ $\mu$J/cm$^2$.

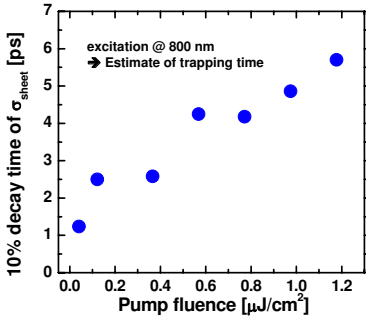


Fig. 4. Estimate of the QD trapping time: 10% decay time constant of the QD SESAM $\Delta\sigma_{sheet}$ traces, as a function of 800-nm pump fluence.

## References


[1] M. Schall and P. Uhd Jepsen, "Photoexcited GaAs surfaces studied by transient terahertz time-domain spectroscopy," Opt. Lett. **25**, 13 (2000).

[2] K. P. H. Lui and F. A. Hegmann, "Ultrafast carrier relaxation in radiation-damaged silicon on sapphire studied by optical-pumpterahertz-probe experiments," Appl. Phys. Lett. **78**, 3478 (2001).

[3] M. Haiml et al., "Optical characterization of semi- conductor saturable absorbers," Appl. Phys. B: Lasers Opt. **79**, 331 (2004).

[4] A. A. Lagatsky et al.,"Low-loss quantum-dot-based saturable absorber for efficient femtosecond pulse generation," Appl. Phys. Lett. **91**, 231111 (2007).

[5] D. Turchinovich et al.,"InAs/GaAs quantum dots as efficient free carrier deep traps ," phys. stat. sol. (c) **0**, 1556 (2003).

[6] D. G. Cooke et al.,"Anisotropic photoconductivity of InGaAs quantum dot chains measured by terahertz pulse spectroscopy," Appl. Phys. Lett. **85**, 3839 (2004).

[7] P. Uhd Jepsen et al.,"Ultrafast carrier trapping in microcrystalline silicon observed in optical pumpterahertz probe measurements," Appl. Phys. Lett. **79**, 1291 (2001).