

# ELECTRON CAPTURE AND RELAXATION IN N-TYPE INAS/GAAS QUANTUM DOTS

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**Abstract** The capture and relaxation processes of electrons in n-type self-assembled InAs/GaAs were investigated using mid-infrared degenerated pump-probe spectroscopy. Fast (~4-10ps) intraband capture/relaxation times were measured even in the complete absence of electron-hole scattering.

**Index Terms** Quantum dots, Infrared spectroscopy, Relaxation processes

## I. INTRODUCTION

An understanding of the capture and relaxation mechanisms in self-assembled quantum dots (QDs) is essential for improving the performance of devices such as quantum dot infrared photodetectors and lasers. To date, most studies have used time resolved photoluminescence or two colour differential transmission (i.e. pump-probe) experiments to determine electron relaxation times in QDs [1,2]. Both of these techniques generate electron-hole pairs during excitation and therefore electron-hole scattering (Auger-type) processes become possible, influencing the electron intraband relaxation. This situation contributes to the continuing

controversy in the interpretation of existing experimental results in this area.

We present a comprehensive investigation of *intraband electron capture and relaxation processes* in the conduction band of InAs QDs. Using a mid-infrared pump-probe (PP) technique we have been able to perform energy dependent and temperature dependent measurements in QD samples containing up to 6 electrons per dot. We find that the electron relaxation time is strongly dependent on the photo-excitation energy and varies from ~4 ps for relaxation from the higher energy excited states inside the QDs up to ~10 ps for relaxation from the wetting layer (WL)/barrier states. Although the ‘phonon bottleneck’ effect predicts the capture time to be much longer (~ 1 ns), the measured times still exceed significantly the typical ~1 ps relaxation time for quantum wells. Also our intraband measurements indicate that the electron capture/relaxation occurs directly to the QD ground state, not step-wise between the QD excited states as has previously been suggested [3]. An advantage of intraband PP is that the QD electron population is determined by the doping, which we vary from 1 up to 6 electrons per dot, allowing the study of relaxation processes in the presence of excess electrons.

## II. EXPERIMENT AND RESULTS

Electron relaxation dynamics from the wetting layer (WL) and the different bound/quasi-bound dot states to the ground state have been studied using either one colour intraband (mid-infrared) pump-probe or two colour interband pump – intraband probe techniques. A femtosecond OPA system (~150 fs pulse width) tuneable between 7  $\mu\text{m}$  and 11  $\mu\text{m}$  was used for one colour PP measurements. In the two colour experiments, a free-electron laser (FEL) tuned to the s-p transition (~60 meV, dotted arrow in Fig.1) was synchronised with a femtosecond Ti:Sapphire laser (tuneable between 800 nm and 840 nm).

Our previous studies have shown that the electron relaxation in QDs from the p-like first excited state to s-like ground state (low energy peak in Fig.1) is typically >30ps [4]. Surprisingly, in the present work, the PP signal corresponding to the relaxation of electrons from higher energy excited states (dashed line in Fig.2) decays with time constant  $\tau$  ~4ps. Such a short decay time strongly suggests that the electron relaxation occurs directly to the ground state, avoiding the p-

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state. When we excite into the WL/barrier states the intraband relaxation time increases to  $\sim 10$ ps for a PP energy of  $\sim 210$ meV. Furthermore, at low temperatures a bi-exponential decay of the PP signal corresponding to electron relaxation from WL/barrier states to QD ground state with  $\tau_1=(8 \pm 2)$  ps and  $\tau_2=(300 \pm 100)$  ps is observed (solid line in Fig.2 and inset). The short decay time is related to electron capture in the same QD from which it was originally excited, whereas the long decay time is strongly dependent on the temperature and originates from the electron capture and thermal re-emission in adjacent QDs.

Temperature dependent measurements were carried out for the sample containing 1 electron per dot. The relaxation time (measured at  $\sim 124$  meV) reduces from  $\sim 3.5$ ps to  $\sim 1.7$ ps upon increasing the temperature from 10 K to 300 K. The relaxation rate dependence on temperature is shown in Fig.3. Electron relaxation via multi-phonon scattering (e.g.  $3LO+1LA$  phonons) does not fit to the experimental data. This result indicates that intraband electron capture and relaxation processes are not determined by multiple-phonon decay but instead are due to other processes, such as polaronic decay.

With an increased number of electrons per dot from  $\sim 1$  to  $\sim 6$  we observed a significant reduction of the relaxation time from  $\sim 4.5$  ps to  $\sim 2$  ps at 10 K due to possible electron-electron scattering processes.

Additionally, interband pump/intraband probe measurements were performed from which the electron capture times from the GaAs barrier and WL states into the QDs of  $\sim 6$ ps and  $\sim 4$ ps, respectively, have been determined. Since interband excitation photo-generates electron-hole pairs, we explain the shortening of the electron capture time by Auger-type electron-hole scattering.

Using a combination of these two techniques we have been able to gain a detailed insight into the electron relaxation processes in QDs, which are significant for quantum dot based lasers and infrared photodetectors. Our results show that, due to the relatively long WL state lifetime ( $\sim 10$ ps), QD infrared photodetectors have the potential to be more efficient compared to quantum well infrared photodetectors.

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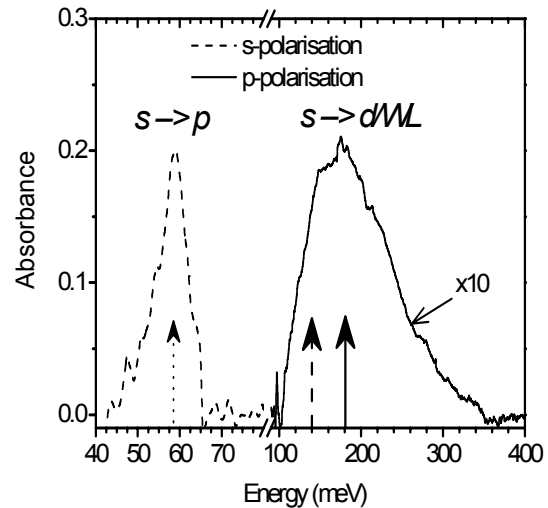


Fig. 1: Low temperature intraband absorption spectrum for QD sample. Arrows show the pump/probe energies.

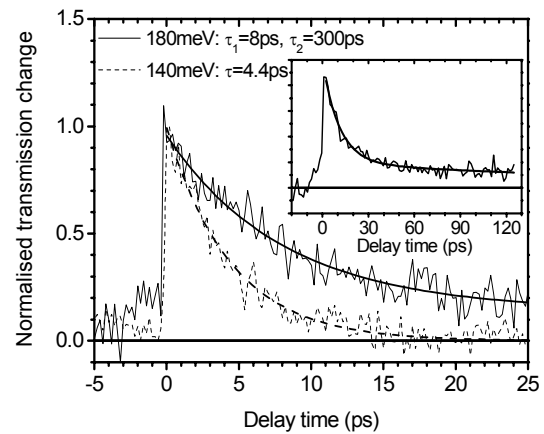


Fig. 2: Normalised PP signals and the best fit for n-type doped sample at 180meV (solid line) and 140meV (dashed line). Inset: the absorption change at 180meV on a larger scale.

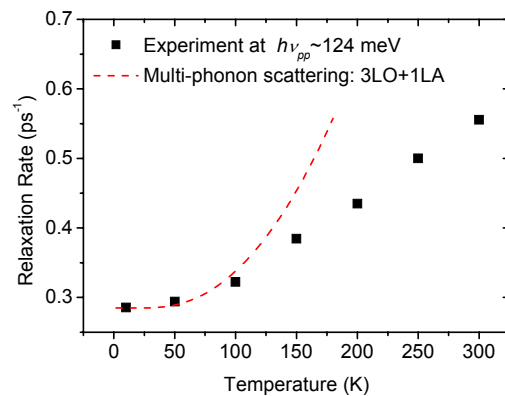


Fig.3: Temperature dependence of the intraband relaxation rate at pump-probe energy of  $\sim 124$  meV (dots) and multi-phonon scattering fit (dashed line).