Ultrafast Intraband Dynamics in InAs/GaAs Quantum Dots

T. Müller, F. F. Schrey, G. Fasching, G. Strasser and K. Unterrainer
Institute of Solid State Electronics, TU Vienna, Austria

The dynamics of carriers in semiconductor quantum dots (QDs) has attracted much attention during the last decade because of their physical interest and their important implications on the performance of novel optoelectronic devices. Most of the experiments have been performed by interband spectroscopy, where the signal reflects the combined electron-hole dynamics. Here we report an interband pump – intraband probe experiment which is sensitive to the capture and relaxation of electrons only [1].

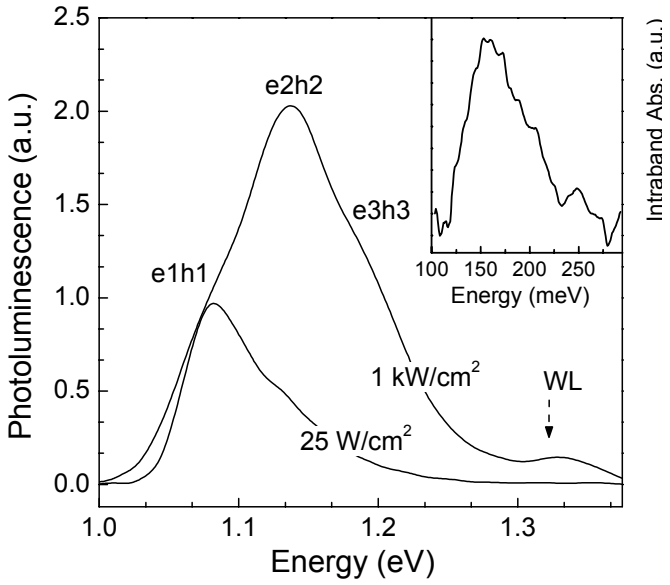

Fig. 1: PL (T = 300 K) spectra at two different excitation densities. Inset: Photo-induced *e*1 – WL intraband absorption spectrum at *T* = 5 K.

The T = 300 K photoluminescence (PL) spectra of the QD sample (30 layers of InAs QDs separated by 50 nm thick GaAs barriers) at excitation densities of 25 W/cm^2 and 1 kW/cm^2 are shown in Fig. 1. We observe three QD transitions, corresponding to *e*1*h*1 emission at 1.081 eV, *e*2*h*2 emission at 1.137 eV and *e*3*h*3 emission at 1.194 eV, as well as luminescence at 1.333 eV from the underlying InAs WL. From the PL we estimate the intraband transition energy between the QD ground state *e*1 and the WL to be ~160 meV. This value is in good agreement with the energy obtained from the photo-induced intraband absorption spectrum shown in the inset. Accordingly, we expect intraband transitions from the excited states *e*2 and *e*3 to the WL at energies of ~105 meV and ~50 meV, respectively. For time-resolved measurements of the intraband transitions we used a mode-locked Ti:sapphire laser that delivers 12 fs pulses (780 nm wavelength). Half of the laser intensity serves as an interband pump to inject electrons and holes in the GaAs barriers. The other part is used to generate the tunable (70 – 155 meV) mid-infrared (MIR) probe pulses by phase-matched difference frequency mixing in a 0.5 mm GaSe crystal.

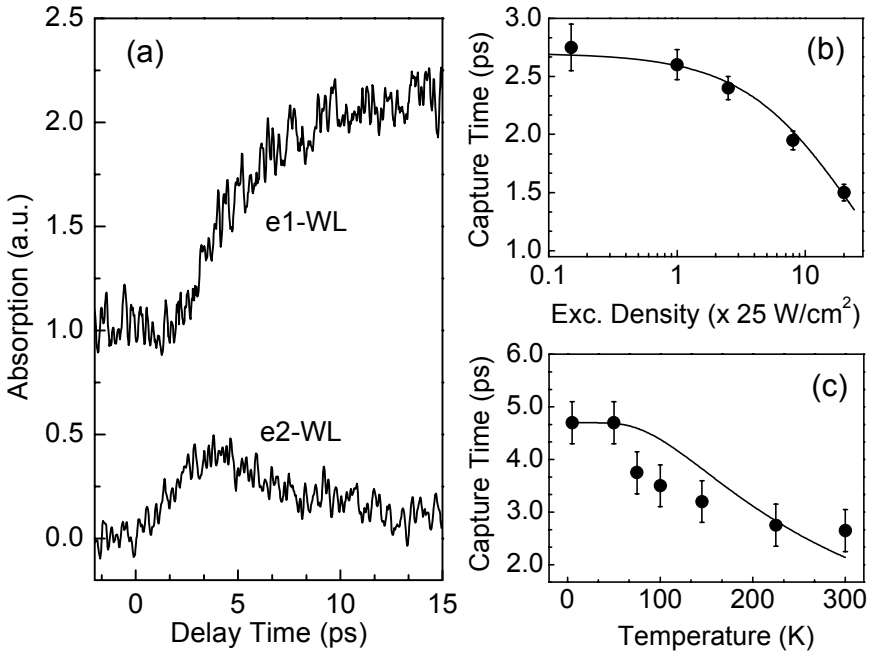

Fig. 2: (a) Photo-induced MIR absorption signals as a function of pump-probe delay at probe energies of 155 meV (upper curve) and 105 meV (lower curve), corresponding to the *e*1 – WL and *e*2 – WL intraband transitions, respectively.
(b) Excitation density dependence and
(c) temperature dependence of the capture time.

Figure 2 (a) shows typical pump-probe signals (I_p = 25 W/cm^2) at T = 5 K when the probe is tuned into resonance with the *e*1 – WL and the *e*2 – WL transition, respectively. After excitation the photo-excited electrons relax very fast into the InAs WL, and from the MIR absorption at different probe energies the QD level populations can be determined. From our measurements we find that the QD ground state *e*1 gets populated via the excited state *e*2, because the electrons leave *e*2 with the same time constant as they arrive in *e*1. As shown in Fig. 2 (b), the excitation density dependence of the capture time exhibits two regimes: At room-temperature it decreases from about 2.7 ps down to 1.5 ps with increasing excitation density above a certain threshold, and it changes only slightly at low excitation densities. The high-power dependence can be explained by electron-electron scattering: An electron is scattered into the QD ground state by transferring its energy to a hot electron in the barrier or the WL. When measuring the temperature-dependence of the capture time we find an increase of τ_c from 2.7 to 4.7 ps upon decreasing the temperature from 300 to 5 K (Fig. 2 (c)). The LO-phonon energy of InAs amounts to E_{LO} = 29 meV and the average electron level separation in our QDs is 55-56 meV. Thus, one possible explanation for the observed short capture times could be that electrons scatter between subsequent QD states via repeated emission of two LO-phonons. The corresponding two-phonon scattering rate for this process can be written $\tau_c^{-1} = \Gamma_0[N_{LO}(T)+1]^2$, where Γ_0 is the scattering rate at T = 0 K and $N_{LO}(T)$ is the Bose–Einstein distribution function for LO phonons. The calculated curve (solid line) can roughly account for the experimental temperature dependence.

References

[1] T. Müller, F. F. Schrey, G. Strasser, and K. Unterrainer, Appl. Phys. Lett. **83**, 3572 (2003).