Photocurrent Spectroscopy of Single InAs/GaAs Quantum Dots

G. Fasching, F.F. Schrey, T. Müller, and K. Unterrainer

Institute of Photonics, Vienna University of Technology, Floragasse 7, A-1040 Vienna, Austria

W. Brezna, M. Austerer, T. Roch, M.A. Andrews, J. Smoliner, and G. Strasser

Institute of Solid State Electronics, Vienna University of Technology, Floragasse 7, A-1040 Vienna, Austria

In this work, we present a carrier escape study from InAs/GaAs self assembled QD's by the use of photocurrent measurements. As a function of the applied field, we detect a shift of the exciton ground state transition due to the quantum-confined Stark shift. From the measured Stark shift S = 4.3 meV we deduce a exciton dipole moment of $p = (4.3 \pm 0.2)\times10^{-29}$ Cm. The tunneling time, which is directly related to the observed photocurrent linewidth due to $\tau \sim \hbar/(2\Gamma)$, changes by a factor of five in the photocurrent regime. The measured linewidth dependency on the electric field is modeled by a simple 1D WKB approximation for the tunneling process, which shows that the energetic position of the wetting layer is important for the measured tunneling time out of the dot.

Introduction

Since the first proposal of quantum dots in 1982 [1] a great deal of research has been dedicated to the study of the optical and electrical properties of QD's. The improved understanding of the excellent properties of this quantum system made it already possible to implement QD's in devices like lasers [2], [3], MIR photodetectors [4], single-photon turnstile devices [5], [6] or single-electron turnstile devices [7]. In previous work [7], [8] a decay of the coherent excitation was observed due to competing mechanisms like carrier-carrier scattering, Coulomb scattering, phonon scattering and tunneling escape.

In this contribution we investigate the influence of these scattering processes on the scattering rate of the observed exciton ground state transition. In our experiments we resonantly excite the exciton interband ground state transition of single InAs/GaAs self-assembled QD's embedded in an *n-i*-Schottky photodiode. QD's provided with both electric contacts and optical access allow us to vary independently the electric field while measuring the electrical or optical response of a single QD. Complementary to the photoluminescence (PL), the collected photocurrent (PC) provides information about the absorption spectrum and the tunneling escape times of single QD's.

Experimental

Sample and Experimental Setup

The sample investigated was grown using molecular beam epitaxy on semi-insulating GaAs (100). Nominally, 1.55 ML of InAs are deposited at 500 °C on *i*-GaAs 40 nm above an *n*-doped GaAs layer (10^{18} cm^{-3}) which forms the bottom contact. During the

growth of the QD's the rotation of the wafer has been stopped to produce an InAs deposition gradient across the wafer, resulting in a variation of the corresponding InAs QD density. Atomic force microscopy (AFM) studies of a similar sample with uncapped dots could determine the density gradient from ~500 µm^{-2} to zero. The growth of the self-assembled QDs is followed by 80 nm *i*-GaAs, a 40 nm thick $Al_{0.3}Ga_{0.7}As$ barrier, and a 10 nm *i*-GaAs cap layer. After the growth the sample was processed by photolithographic methods into photodiodes. Ohmic contacts were established to the doped n^+ region and semitransparent Ti-Schottky contacts were deposited on the top surface to achieve a homogeneous electric field in the region of the investigated QD's. The Schottky contact was in addition covered with an opaque Au mask where 2 µm^{-2} apertures were opened to allow optical access to the QDs. The results reported in the present work were obtained from a region of the wafer where the QD density I < 1 µm^{-2}.

The PL and the PC measurements were performed at 4.2 K using the 760 nm line of a cw Ti:Sapphire laser for PL spectroscopy and a tunable Ti:Sapphire laser to resonantly excite the QD energy levels for PC spectroscopy. The sample was placed in a low drift Oxford LHe flow cryostat. The PL and PC excitation paths as well as the PL detection path lead through a confocal laser scanning microscope (LSM) with a lateral and axial resolution below 500 nm. The PL signal is filtered by an 850 nm long pass filter and dispersed in a 0.5 m spectrometer, which allows a spectral resolution better than 50 µeV with a liquid nitrogen cooled CCD detector. The PC signal is detected by a sensitive photodiode amplifier which is capable to bias the photodiode and standard lock-in technique. The spectral resolution of the PC measurements determined by the laser linewidth is ≈30 µeV.

Measurements

The band structure under negative bias condition is shown schematically in Fig. 1. Changing the bias voltage from positive to negative voltage reduces the tunneling barrier thickness in the direction of the applied field and therefore the tunneling time τ_t of the photoexcited carriers out of the dot. When τ_t becomes equal or even smaller than the radiative lifetime of the exciton τ_r ~ 1 ns one changes from the PL measurement regime to the PC measurement regime.

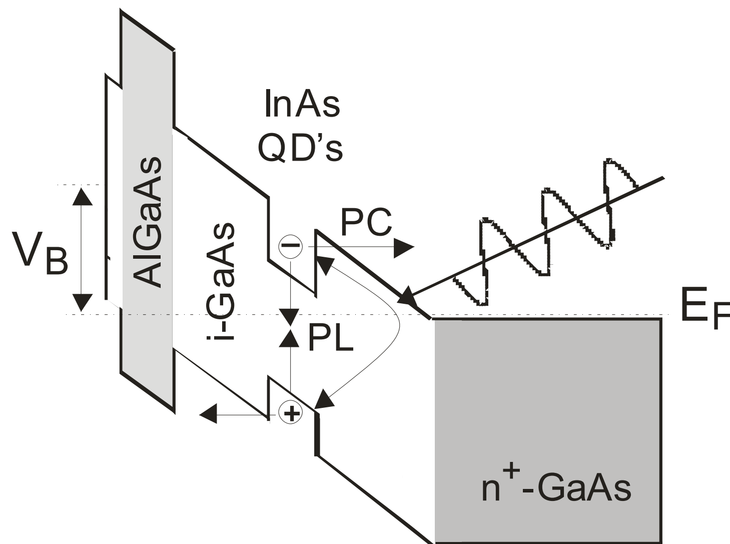

Fig. 1: Schematic band diagram of the investigated Schottky photodiode under negative bias voltage V_B

Figures 2 (a) and (b) show PL and PC spectra at the same aperture of the shadow mask under different bias conditions. In both cases sharp single peaks are observed attributed to single QD emission (PL) and absorption (PC). The PC line in Fig. 2 (b) is measured at higher electric field than the PL line in Fig. 2 (a) and is therefore shifted to a lower energy due to the QCSE. Under the measurement conditions shown in the inset of Fig. 2 (b) the observed PC peak magnitude is 2.5 pA. This current corresponds to a generation rate of 10^7 e-h pairs per second. The fact that no biexciton lines are observed, which have typically about 3 meV binding energies, leads to the conclusion that the used excitation power was low enough that occupation of the QD with more than one exciton can be excluded. The FWHM of the PL line corresponds (according to $\tau \sim \hbar/(2\Gamma)$) to an exciton lifetime τ of about 6 ps which is approx. three orders of magnitude smaller than the radiative lifetime of 1 ns mentioned above. This effective lifetime is given by $\tau^{-1} = \tau_r^{-1} + \tau_t^{-1} + \tau_c^{-1}$, where τ_r is the recombination time, τ_t is the tunneling time and τ_c^{-1} describes Coulomb scattering by free carries (due to the nonresonant excitation for PL), defects, impurities, and alloy fluctuations. The PC linewidth is limited to ~100 µeV for low electric fields where also PL can be measured. Due to these findings we claim that the FWHM of the measured PC and PL lines is limited due to the Coulomb interactions mentioned above. The PC signal can be observed in the electric field range of 30 kV/cm to 80 kV/cm.

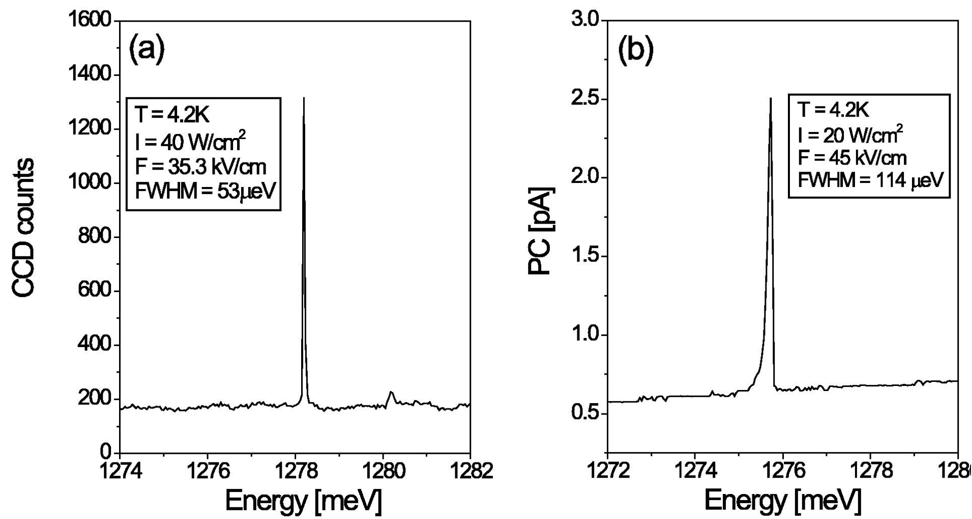

Fig. 2: Photoluminescence (a) and photocurrent (b) spectrum of a single QD. The energetic shift is due to the Stark shift and bias-controlled charging of the QD at low electric fields where the QD ground state level is shifted below the Fermi level [9].

Conclusion

In this contribution we report on field-dependent photocurrent measurements of the excitonic interband transitions of single InAs/GaAs self-assembled QD's. The application of an external electric field allows controlling the transition energy due to the QCSE. The measured Stark shift S = 4.3 meV/V of the exciton transition can be used for the realization of a single QD spectrometer. From the measured Stark shift we obtain a dipole moment $p = (4.3 \pm 0.2)\times 10^{-29}$ Cm. The decrease of the PC linewidth for low electric fields is limited to a value of $\Gamma \sim 100$ µeV, which is attributed to Coulomb interaction of the exciton with carriers surrounding the QD.

Acknowledgements

The authors acknowledge financial support by the Austrian Science Fund (FWF), SFB-ADLIS and START Y-47.

References

[1] Y. Arakawa and H. Sakaki, *Appl. Phys. Lett.* **40**, 939 (1982).

[2] G. Park, O.B. Shchekin, D.L. Huffaker, D.G. Deppe, *IEEE Photon. Tech. Lett.* **12**, 230 (2000).

[3] N.N. Ledentsov, A.R. Kovsh, A.E. Zhukov, N.A. Maleev, S.S. Mikhrin, A.P. Vasil'ev, E.S. Semenova, M.V. Maximov, Yu.M. Shernyakov, N.V., Kryzhanovskaya, V.M. Ustinov, D. Bimberg, *IEEE Electron. Lett.* **39**, 1126 (2003).

[4] L.Rebohle, F.F. Schrey, S. Hofer, G.Strasser, K. Unterrainer, *Appl. Phys. Lett.* **81**, 2079 (2002).

[5] P. Michler, A. Kiraz, C. Becher, W.V. Schoenfeld, P.M. Petroff, Lidong Zhang, E. Hu, A. Imamoglu, *Science* **290**, 2282 (2000).

[6] Z. Yuan, B.E. Kardynal, R.M. Stevenson, A.J. Shields, C.J. Lobo, K. Cooper, N.S. Beattie, D.A. Ritchie, M. Pepper, *Science* **295**, 102 (2002).

[7] A. Zrenner, E. Beham, S. Stufler, F. Findeis, M. Bichler, G. Abstreiter, *Nature* **418**, 612 (2002).

[8] X. Li, Y. Wu, D. Steel, D. Gammon, T.H. Stievater, D.S. Katzer, D. Park, C. Piermarocchi, and L.J. Sham, *Science* **301**, 809 (2003).

[9] F. Findeis, M. Baier, E. Beham, A. Zrenner, and G. Abstreiter, *Appl. Phys. Lett.* **78**, 2958 (2001).