Dephasing of Polarons in InAs/GaAs Self-Assembled Quantum Dots

Evgeny A. Zibik, Ben A. Carpenter, Luke R. Wilson, John W. Cockburn
Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
Email: e.zibik@sheffield.ac.uk
Email: luke.wilson@sheffield.ac.uk

P. Jonathan Phillips, Nguyen Q. Vinh
FOM Institute Rijnhuizen, PO Box 1207, NL-3430BE, Nieuwegein, Netherlands

Matthew J. Steer, and Mark Hopkinson
EPSRC National Centre for III-V Technologies, Department of Electronics & Electrical Engineering, University of Sheffield, Sheffield, S1 3JD, UK

Abstract: Polaron dephasing processes are investigated using far-infrared degenerate four wave mixing. Long (~80ps) dephasing times are measured and a clear change from phonon-mediated to Auger-mediated dephasing is observed as the dot carrier population increases.

OCIS codes: (190.4380) Nonlinear optics, four-wave mixing; (190.7110) Ultrafast nonlinear optics; (300.2570) Four-wave mixing; (300.6290) Spectroscopy, four-wave mixing; (300.6530) Spectroscopy, ultrafast;

1. Introduction

Recent experimental [1] and theoretical [2, 3] studies have demonstrated that the interaction between electrons and phonons in quantum dots (QDs) can only be described by considering them to be in the strong coupling regime, forming polarons. To date, ultrafast measurements in this area have concentrated on studying the polaron decay process [4, 5], which has been shown to occur on a long timescale (tens of ps), relative to intraband carrier relaxation in quantum wells (ps timescale). These studies have also identified the polaron decay mechanism and show a monotonic increase of the decay time with increasing energy, providing clear evidence of a strong coupling regime in which the 'phonon-bottleneck' does not exist. The long relaxation time highlights the potential of QD-based mid-infrared intraband detectors and emitters, which require long excited state lifetimes for efficient operation.

We will present a detailed investigation of polaron dephasing processes in n-type InAs quantum dots (QDs) using energy and temperature dependent, far-infrared degenerate four wave mixing (FWM). Our measurements allow us to determine the polaron dephasing time and hence the homogeneous linewidth. At these far-infrared wavelengths it is not possible to obtain the homogeneous linewidth by direct, single QD measurements due to the small QD absorption and relatively insensitive detectors. We show that the dephasing time has a similar energy dependence to the polaron decay time, increasing with increasing detuning from the optical phonon energy. Upon increasing the QD carrier population we observe a clear change from a phonon-mediated dephasing process to one which is dominated by Auger-type dephasing.

2. Experimental results

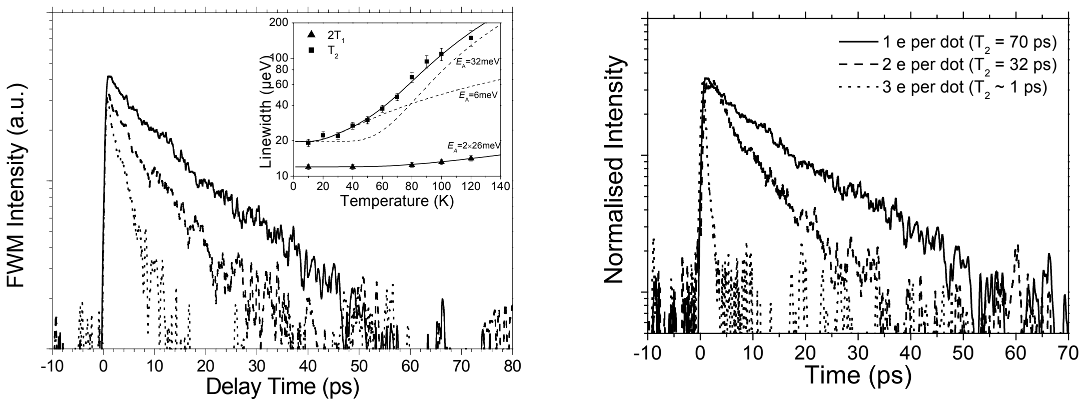
Coherent polaron polarizations in QDs were studied using a standard two-pulse photon echo arrangement in a non-collinear geometry [6]. The phase-matched signal was detected in the $2\cdot\mathbf{k}_2-\mathbf{k}_1$ direction. The far-infrared time-integrated FWM measurements were carried out using the Dutch free electron laser (FELIX) which provides tunable far-infrared laser pulses of ~1ps duration.

For excitation in resonance with the QD ground to first excited conduction band transition, we find low temperature dephasing times T_2 ~80 ps (Fig. 1), approximately two orders of magnitude longer than T_2 for intersubband transitions in quantum wells. From the measured T_2 time at 10K, we extract a homogenous linewidth Γ_{hom}~20 μeV, approximately 0.4% of the predominantly inhomogeneously broadened linewidth of (Γ_{inhom}~5 meV) measured using linear absorption.

We also found that the polaron dephasing time decreases from ~80 ps at excitation energy $\hbar\omega \approx 53$ meV to ~60 ps at $\hbar\omega \approx 48$ meV. This is consistent with the energy dependence of the polaron decay time [3, 5], which decreases as the polaron energy approaches that of the LO-phonon.

1-55752-813-6/06/$25.00 ©2006 IEEE

As shown in the inset of Fig. 1a, temperature dependent studies reveal that, for samples doped to contain one electron per dot, polaron dephasing is phonon mediated and involves both low energy acoustic phonons and high energy optical phonons. This behavior is similar to that observed for exciton dephasing [7] and is very different from the weak temperature dependence of the polaron decay time (T_1) over the same energy range (Fig. 1a inset), which we have previously shown arises from polaron decay to two high energy acoustic phonons [5].



(a) (b)

Fig. 1. (a) Temperature dependent four wave mixing signals at 20K (solid line), 50K (dashed line) and 80K (dotted line), excited in resonance with the ground to first excited state intersublevel transition. The inset shows temperature dependence of the polaron linewidth. (b) Normalized four wave mixing signals for samples doped to contain 1 electron (solid line), 2 electrons (dashed line) and 3 electrons (dotted line) per dot.

The use of intersublevel excitation also allows us to study excited state dephasing for samples doped with two or more electrons per dot, a regime which is difficult to access using interband excitation due to Pauli blocking of the QD ground state. We find a dramatic reduction in T_2 for samples doped to contain more than one electron per dot (Fig. 1b). This result gives a clear indication that there is a transition from a phonon mediated dephasing process to one which is due to carrier-carrier interactions as the QD population increases, in contrast to quantum wells where intersubband dephasing is always dominated by carrier-carrier interactions.

[1] S. Hameau, Y. Guldner, O. Verzelen, R. Ferreira, G. Bastard, J. Zeman, A. Lemaitre, and J.M. Gerard, “Strong electron-phonon coupling regime in quantum dots: Evidence for everlasting resonant polarons,” Phys. Rev. Lett. **83**, 4152-4155 (1999).
[2] T. Inoshita, and H. Sakaki, “Density of states and phonon-induced relaxation of electrons in semiconductor quantum dots,” Phys. Rev. B **56**, R4355-R4358 (1997).
[3] X.-Q. Li, H. Nakayama, and Y. Arakawa, “Phonon bottleneck in quantum dots: Role of lifetime of the confined optical phonons,” Phys. Rev. B **59**, 5069-5073 (1999).
[4] S. Sauvage, P. Boucaud, R.P.S.M Lobo, F. Bras, G. Fishman, R. Prazeres, F. Glotin, J.M. Ortega, and J.M. Gerard, “Long polaron lifetime in InAs/GaAs self-assembled quantum dots,” Phys. Rev. Lett. **88**, 177402 (2002).
[5] E.A. Zibik, L.R. Wilson, R.P. Green, G. Bastard, R. Ferreira, P.J. Phillips, D.A. Carder, J-P.R.Wells, J.W. Cockburn, M.S. Skolnick, M.J. Steer, and M. Hopkinson, “Intraband relaxation via polaron decay in InAs self-assembled quantum dots,” Phys. Rev. B **70**, 161305(R) (2004).
[6] D. Zimdars, A. Tokmakoff, S. Chen, S. R. Greenfield, M. D. Fayer, T. I. Smith, and H. A. Schwettman, “Picosecond infrared vibrational photon echoes in a liquid and glass using a free electron laser,” Phys. Rev. Lett. **70**, 2718 (1993).
[7] P. Borri, W. Langbein, U. Woggon, V. Stavarache, D. Reuter, and A. D. Wieck, “Exciton dephasing via phonon interactions in InAs quantum dots: Dependence on quantum confinement,” Phys. Rev. B **71**, 115328 (2005).