Intraband Auger Effect in InAs/InGaAlAs/InP Quantum Dot Structures

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Intraband photocurrent and absorption measurements were performed on InAs/InGaAlAs/InP quantum dot structures. A full three-dimensional theoretical model has been employed to identify the observed PC as a bound to bound transition, where the final state is about 200 meV deep below the conduction band continuum. The reported results strongly suggest that an Auger process plays a fundamental role in generating the observed intraband photocurrent.

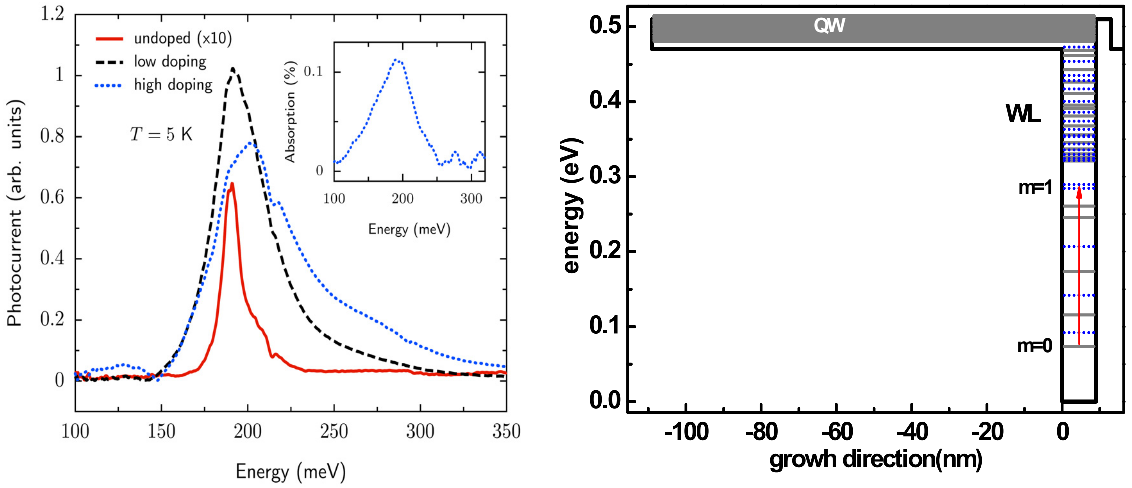
Introduction

Semiconductor quantum dot (QD) structures have raised much interest in the past years for application in mid-infrared photodetection due to their potential for efficiently coupling normal incident light and for higher operation temperature as compared to quantum well structures [1] – [6]. For most of the QD structures the intraband optical transitions occurs in the 5-20 µm range between a bound to bound or a bound to quasibound state. Beside the fact that they produce more selective detectors, they require an extra carrier transport mechanism to generate the observed photocurrent (PC) and this is attributed to thermal excitations even for deep final bound states [1] – [4]. Another possibility to extract the carriers from the final bound energy state to the continuum, where they can easily participate in the PC, is via an Auger effect.

Theoretical studies in the 90's showed that inter- and intraband Auger scattering in quantum dots are very effective processes [7]. The activation of photoexcited electrons by Auger scattering in interband transitions has been shown experimentally for InAs/InP QD structures [2] and Auger scattering in undoped and n- and p-type doped InGaAs quantum dots was theoretically investigated in [9]. However, experimental evidence of the Auger effect on intraband transitions has not yet been reported. In this communication we present results that demonstrate that Auger processes can indeed play a fundamental role in generating an intraband PC, broadening the possibilities for designing QD structures for highly selective mid-infrared photodetectors.

Experiment and Discussion

The samples under investigation are grown on a 150 nm thick InP buffer layer deposited at 630 °C on a semi-insulating InP substrate followed by a 500 nm thick n-doped lattice matched InGaAs layer acting as the bottom contact. Afterwards a 109 nm thick lattice matched layer of InGaAlAs is grown with 16% Al content. The InAs QDs are then deposited for 5.5 s at 520 °C and they are annealed in an arsine atmosphere for 12 s. They are covered by a 16 nm thick InP layer while the temperature is ramped up to 600 °C. This sequence is repeated for 10 times. A last 109 nm thick layer of the quaternary material is then grown and finally a 250 nm *n*-doped InGaAs contact layer is deposited. The doping level at the contact layers is 1.0 x 10^{18} cm^{-3}. All ternary and quaternary layers are grown at 600 °C. The QD samples were grown with three different doping levels: one nominally undoped sample and 2 samples with 2 and 4 electrons respectively. The composition of the quaternary material was chosen so as to maximize the dot density [11]. Using atomic force microscopy (AFM) average dot height and density of 9 nm and 1.5 x 10^{10} respectively has been measured on uncapped QD control samples. Transmission electron microscopy (TEM) images showed lens shaped QDs with a base diameter of approximately 60 nm and confirmed the QD height average of 9 nm.

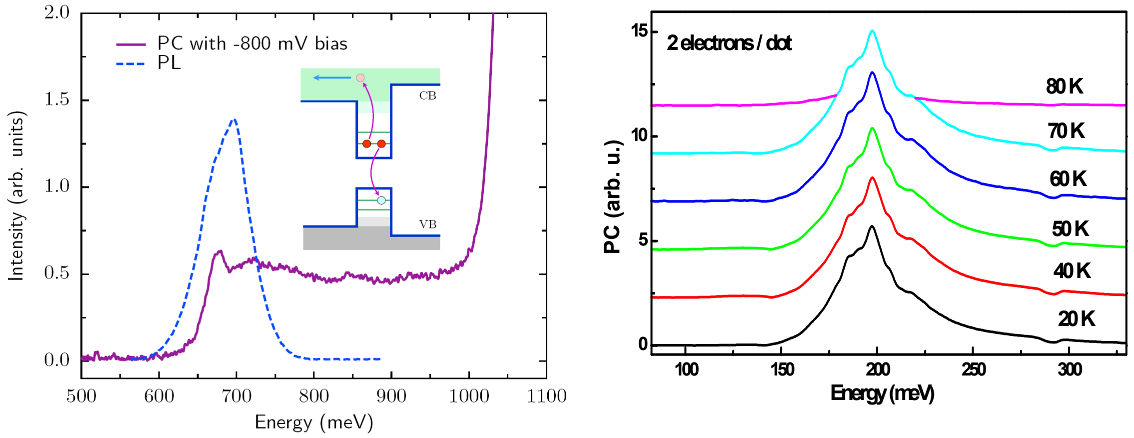


(a) (b)

Fig. 1: (a): PC response for different doping; the inset shows the absorption with respect to InP substrate at 5K. (b): Conduction band structure profile and calculated energy levels for the investigated samples for quantum numbers *m* = 0 (solid lines) and *m* = 1 (dashed lines). The arrows show the optical transitions for which the oscillator strength is largest. The WL-layer states are also shown.

Photocurrent (PC) and absorption measurements were performed using Fourier Transform Infrared Spectroscopy (FTIR). Figure 1 (a) shows the photocurrent spectra at 5 K for the investigated samples measured with the FTIR with normal incident light and no external bias. A narrow PC peak is observed around 190 meV for the undoped sample. The sample is nominally undoped, but the presence of residual doping and carrier diffusion from the contacts leads to a population of the QD so that intraband absorption can occur. A ten times stronger and three times broader signal was observed for the same structure with a doping of about 2 and 4 electrons per dot. The broadening of the PC-peak as a function of doping can be explained by the inhomogeneous broadening of the quantum dot sizes. The ground state of large QD lies deeper in energy, so if the doping is low, only a small fraction of the QDs get populated. But broadening also occurs if higher QD states get populated due to higher doping. Absorption measurements were performed in order to confirm the results. They where done in waveguide geometry using the same structures as for the PC measurement but with 20 layers instead of 10 layers. A peak centered around 185 meV – 195 meV has been observed in nice agreement with the PC spectra (inset Fig. 1 (a)).

An effective mass model was applied in a theoretical calculation assuming lens shape for the QD (according to the TEM images) and where the physical parameters were taken from [12]. A more sophisticated treatment about the theoretical model can be found in [11]. The results of the calculations can be seen in Fig. 2 (b). The solutions for the quantum numbers 0 (solid line) and 1 (dashed line) are superimposed to the QD structure profile. The transition between the ground state and the fourth excited state, corresponding to energy of 197 meV, turned out to be the strongest. For the absorption of normal incoming light a change in angular momentum is necessary. Now the important point to note is that the final state of this transition is still 200 meV from the continuum that implies that the excited electrons cannot contribute directly to the PC.



(a) (b)

Fig. 2: (a): PL (solid line) and interband PC (dotted line) spectra for the undoped sample at 80 K. PC spectra at 70 K (dash-dotted line) and 60 K (dashed line) are also shown. The inset illustrates the intraband and interband Auger. (b): Temperature dependence of the medium doped sample. The amplitude stays constant up to 70 K.

Comparing the photoluminescence (PL) (Fig. 2 (a), dashed line) with the interband PC (solid line) at 80 K a clear contribution from the QDs can be observed around 700 meV. This gives further support that the intraband PC comes from the absorption of a transition deep inside the QD. As has been clamed by Landin et al. [8] the interband PC from the QDs is produced by an interband Auger effect, where the photo-excited electron receives additional energy from the recombination of another electron with the photogenerated hole. A scheme of such a process is depicted in the inset of Fig. 2 (a).

The final state of the intraband transition that produces the PC is 200 meV below the contiunuum. The thermal energy is very small at low temperature so that thermal assisted extraction of such photo-excited carriers gets inefficient. The amplitude of the PC as a function of temperature shows nearly no dependence on temperature between 5 and 60 K (Fig. 2 (b)). This behavior can be explained by Auger scattering as a temperature independent process. A photo-excited electron can be promoted to the continuum by an energy transfer from an electron that relaxes from a higher energy state down to the ground state. The suggested intraband Auger scattering can be seen schematically in in the inset of Fig. 2 (b). The theoretical calculation showed that there are many possible states available to participate to this process. One should also consider that the FTIR measurement is done with a broadband light source that increases the possibility to have two electrons in a dot simultaneously excited.

Dynamical processes in the device could cause a non-vanishing population of higher states. The dark current in the devices is a result of thermal emission and re-capture of electrons. Time resolved measurements showed that electron capture occurs very fast into high lying states and is then slowed down for lower lying states [13]. As a consequence we can expect that higher lying states are populated.

Conclusion

In summary, we have carried out a detailed study of the intraband optical response of quantum dot structures for mid-infrared photodetection in order to verify the possibility of carriers in a rather deep bound state generating a photocurrent. The obtained photocurrent and absorption results, together with a realistic theoretical calculation, strongly suggest that an Auger process can produce a significant current. Photoluminescence together with interband photocurrent further supports this attribution. The reported results indicate that quantum dot photodetector structures could be designed to operate based on the more selective bound-to-bound transitions of quantum dots and still produce an efficient device.

Acknowledgements

We thank I. G. Solórzano and H. F. Filho for the TEM and AFM measurements. This work has benefited from fruitful discussions with G. Bastard. Financial support from the WPI, FWF SFB IR-ON, EC NoE SANDIE, CAPES, CNPq, FINEP, FAPERJ and FAPEMIG is acknowledged. JVB is supported by the Alexander von Humboldt Foundation.

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