

The issue of 0D-like ground state isolation in GaAs- and InP-based coupled quantum dots-quantum well systems

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Abstract. The issue of quantum mechanical coupling between a semiconductor quantum dot and a quantum well is studied in two families of GaAs- and InP- based structures at cryogenic temperatures. It is shown that by tuning the quantum well parameters one can strongly disturb the 0D-character of the coupled system ground state, initially located in a dot. The out-coupling of either an electron or a hole state from the quantum dot confining potential is viewed by a significant elongation of the photoluminescence decay time constant. Band structure calculations show that in the GaAs-based coupled system at its ground state a hole remains isolated in the dot, whereas an electron gets delocalized towards the quantum well. The opposite picture is built for the ground state of a coupled system based on InP.

1. Introduction

The coupling between semiconductor self-assembled quantum dots (QDs) and a quantum well (QW) is considered as an essential process that would bring new functionalities to electronic or optoelectronic devices. In the concept, a QW serves as a carrier mobility channel that can mediate the charge or spin exchange process between a QD state ultimately defined in the real space. The coupling is a purely quantum mechanical effect where QDs are separated from a QW by a thin enough barrier, allowing charge or spin tunneling between subsystems. Although, the idea is simple in its form, however, to achieve a certain functionality one need carefully guide the engineering process of the coupled QDs-QW (CQDsQW) system to avoid undesirable consequences of the coupling. A striking example is the necessity to preserve an isolated 0D-like character of the QD state in the environment determined by the electronic coupling. Such state is of primary importance for many applications based on the CQDsQW concept. One can only mention tunnel injection lasers[1, 2] or spin memory devices[3]. In the first example, the coupling results in an efficient carrier redistribution process among a dense ensemble of QDs but to get



benefits from the QDs as a laser gain medium one need assure the 0D-like density of states for the lasing state. In the case of a spin memory device, the QW plays a role of the information highway that can address a QD memory element. However, the spin state must be efficiently isolated from other states acting as a source of decoherence.

This work reveals the issue of losing the isolated character of the QD-like ground state (GS) in the CQDsQW system that can be observed in two technologically important material systems based on GaAs and InP. The work is experimental, with the leading role of time-resolved photoluminescence spectroscopy (TRPL), supported by photoluminescence (PL), and modulated reflectivity ($\Delta R/R$), but also theoretical calculations of the CQDsQW band structure.

2. Experimental details and methodology

Investigated CQDsQW structures were grown by molecular beam epitaxy either on a semi-insulating (001)GaAs or a sulfur-doped (001)InP substrate.

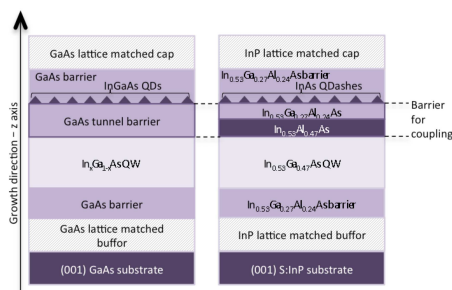


Figure 1. The layer sequence of coupled QDs-QW structures based on GaAs (left hand side) and InP substrate (right hand side).

The layer sequence for considered systems is depicted in Fig. 1 and the growth details are presented in Ref.[4, 5]. QDs are different in both material systems. The (In,Ga)As/GaAs QDs are quite typical, with a pyramidal shape of 16 nm in the base length and 1.7 nm in height. For such dots, the GS energy is centered at ~ 1.22 eV. The InAs/InGaAlAs/InP QDs are strongly elongated in one of the in-plane direction, having a triangular cross section, with the base width of ~ 30 nm and height of ~ 3.5 nm.[6] The typical length of the dot exceeds 150 nm, which is why these structures are sometimes called quantum dashes (QDashes). The ground state in these structures is centered near 0.85 eV, right at the third telecom window. The coupling between the QW and QD GSs is tuned by adjusting parameters of the well, while keeping the barrier width constant (2 nm). With the QW parameters of $d=15$ nm (well width), and the [In] content $x=0.17$, the GaAs-based CQDsQW GS is nominally uncoupled, as compared to the coupled structure with $d=7$ nm and $x=0.23$. For the InP-based structure, the nominally uncoupled CQDsQW GS is obtained for $d=4.5$ nm as compared to the coupled one, with $d=6.5$ nm. In both cases, the chemical content of the well remained unchanged.

For the continuous-wave (CW) PL, $\Delta R/R$, and TRPL experiments, the structures were held at $T=4.2$ K in a He-flow cryostat. The 532 nm line from the YAG laser was used as a source of photo-excitation in the CW regime. For the TRPL experiment, structures were excited by a train of 140-fs long pulses, at a repetition frequency of 76 MHz generated by the Ti:Sapphire oscillator. Subsequent PL emission was dispersed by a 0.3-m-focal-length monochromator and detected by a streak camera system equipped either with the S1 or liquid nitrogen-cooled NIR photocathode. The CW PL was measured in the same setup, with the InGaAs linear array detector. Details of the PR experiment are described in Ref.[6, 7].

Calculations of the CQDsQW system band structure was performed in the 3D eight-band \mathbf{kp} model[4, 8], whose implementation includes strain fields and piezoelectric effects.

3. Results and discussion

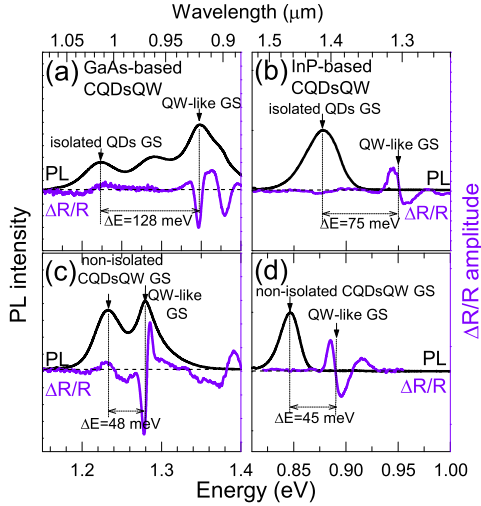


Figure 2. (a) PL and $\Delta R/R$ spectra for the GaAs-based CQDsQW system with the uncoupled ground state isolated within a QD, and (b) its InP-based counterpart. (c) PL $\Delta R/R$ spectra for the GaAs-based CQDsQW system with the coupled GS, and (d) its InP-based counterpart. $T=4.2$ K

The PL spectra for CQDsQW structures characterized by the uncoupled and coupled GS are depicted in Fig. 2 (black line). Since the coupling at the GS is hard to parametrize, one can use the ΔE value that defines the energy distance between the CQDsQW GS and the first QW-like GS transition revealed as a well visible absorption-like feature in the $\Delta R/R$ spectrum in Fig.2(violet line). The significant value of ΔE may indicate that the presence of the QW confining potential disturbs only the higher lying states of a QD, while the coupled system GS remains isolated in a dot. The TRPL experiment confirms the hypothesis. The PL lifetime measured at the GaAs-based CQDsQW GS is ~ 1 ns and ~ 2 ns for the InP-based structure with a large ΔE . Both numbers are similar to those presented for typical QDs/QDashes for a material system considered here. By modifying the QW parameters for specified application purposes, one can obtain a much deeper confining potential of the well. Its presence may obviously disturb the lowest lying states of a QD. It can happen for the structures with small ΔE presented in Fig. 2 (c) and (d). In this case, the lack of isolation of a QD GS may result in the out-coupling of the particle probability density function from the confining potential of the dot. This, however, would be translated into an elongated PL decay time measured at the CQDsQW GS. Indeed, the PL decay time increases from ~ 1 ns to ~ 1.9 ns for the GaAs-based structure when such out-coupling is expected. A similar behavior is observed for the InP-based counterpart, where the decay time increases from ~ 2 ns to ~ 10 ns. Although experimental evidence for the lack of 0D-like isolation at the coupled system GS seems to be clear for specific QW parameters, there is still a question concerning the outcoupling nature in both investigated material systems. To address this issue, one can perform the band structure calculations of CQDsQW system.

Figure 4 shows potential band profiles for GaAs- and InP-based CQDsQW systems in the absence (Fig. 4(a),(c)) and presence of the GS coupling (Fig. 4(b),(d)). One can see that in the

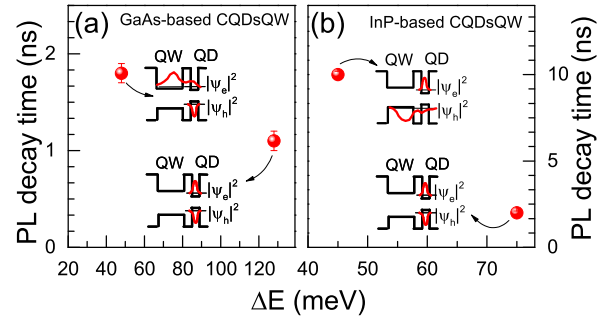


Figure 3. PL decay time obtained for GS emission of (a) GaAs-based CQDsQW system, and (b) InP-based one. $T=4.2$ K and non-resonant excitation at 830 nm. The idea concerning the lack or presence of isolation of the CQDsQW system GS is depicted in sketches. $|\Psi_e|^2$ and $|\Psi_h|^2$ are single particle, electron and hole density probability functions.

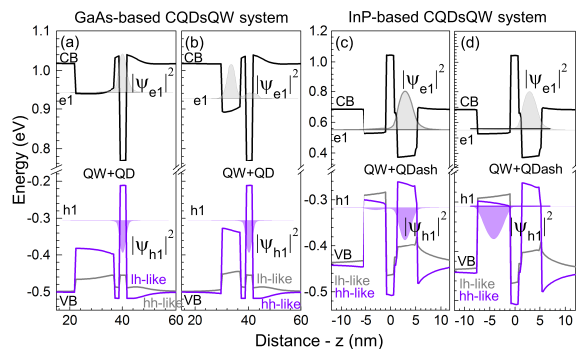


Figure 4. Calculated band structure for GaAs- and InP-based CQDsQW with QW parameters (a) $d=15$ nm, In content: $x=0.17$, (b) $d=7$ nm, $x=0.23$, (c) $d=4.5$ nm, (d) $d=6.5$ nm. $|\Psi_{e1,h1}|^2$ are single particle, electron or hole, probability density functions, CB and VB are conduction and valence bands for two types of holes (hh-like, lh-like).

case of the GaAs-based system, a hole state is isolated in the dot, whereas an electron one is smeared over the QD and QW potential. Surprisingly, the opposite picture appears for the InP-based coupled system. In this case an electron state is effectively localized within the dot/dash structures, whereas a hole is delocalized among the effective potential created by the dot/dash and the QW.

4. Conclusions

The required coupling between a semiconductor QD and a QW makes a design process of the coupled QD-QW system quite challenging. Tuning the QW parameters towards achieving certain functionality of a device may lead to the loss of the 0D-like character of the coupled system GS, initially restricted to a QD. Moreover, depending on the material system, the nature of the out-coupling of the fundamental state can have a different origin. While in the GaAs-based coupled system there is a high chance to out-couple the electron state, keeping the hole one localized, in the InP-based systems the effect is exactly opposite. These results show that the design process of devices based on CQDsQW architecture is very demanding and needs a closer look, especially at material parameters, such as band offsets, to obtain expected benefits.

Acknowledgments

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References

- [1] G. Walter, N. Holonyak Jr., J. H. Ryou, and R. D. Dupuis 2001 *Appl. Phys. Lett.* **79** 1956
- [2] Z. Mi, S. P. Bhattacharya, and S. Fathpour 2005 *Appl. Phys. Lett.* **86** 153109
- [3] A. Marent, T. Nowozin, M. Geller, and D. Bimberg 2011 *Semicond. Sci. Technol.* **26** 014026.
- [4] M. Syperek, J. Andrzejewski, W. Rudno-Rudziński, G. Sęk, J. Misiewicz, E. M. Pavelescu, C. Gilfert, and J. P. Reithmaier 2012 *Phys. Rev. B* **85** 125311
- [5] W. Rudno-Rudziński, M. Syperek, J. Andrzejewski, A. Maryński, J. Misiewicz, A. Somers, S. Höfling, J. P. Reithmaier, and G. Sęk 2017 *AIP Adv.* **7** 015117
- [6] W. Rudno-Rudziński, R. Kudrawiec, P. Podemski, G. Sęk, J. Misiewicz, A. Somers, R. Schwertberger, J. P. Reithmaier, and A. Forchel 2006 *Appl. Phys. Lett.* **89**, 031908
- [7] J. Misiewicz, P. Sitarek, G. Sęk, and R. Kudrawiec 2003 *Mater. Sci.* **21** 263
- [8] J. Andrzejewski, G. Sęk, E. O'Reilly, A. Fiore, and J. Misiewicz 2010 *J. Appl. Phys.* **107** 073509