Highly Linearly Polarized Emission from Quantum Dash Excitons
Modelling and Experiment at the 3rd Telecom Window

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Abstract: This work is focused on controlling the polarization anisotropy of emission from single self-assembled InAs/InGaAlAs quantum dashes grown by molecular beam epitaxy on InP substrate. We studied the degree of linear polarization of excitonic emission for submicrometer mesa photonic structures of asymmetric in-plane geometry. We present both experimental and numerical analysis performed at 1550 nm wavelength (3rd telecommunication window for optical fibers), and we discussed the impact of anisotropy of the dielectric confinement, which paves the way towards a single photon source characterized by a degree of linear polarization exceeding 0.9.

1 INTRODUCTION

Single nanostructures like quantum dots or dashes embedded in semiconductor matrix have been found as promising candidates for quantum emitters such as single photon sources (Michler *et al.*, 2000; Fiore *et al.*, 2007; Dusanowski *et al.*, 2014) or entangled photon pairs (Akopian *et al.*, 2006; Stevenson *et al.*, 2006). By modifying their external environment, one can obtain enhancement or inhibition of spontaneous emission rate due to Purcell effect (Purcell, 1946). Advanced microstructures allow also for controlling the polarization state of the emitted light when transition dipole moment of excitons couples with the optical far field modes (Munsch *et al.*, 2012; Foster *et al.*, 2015). By measuring the polarization anisotropy of emission, it is possible to analyse the coupling selectivity in terms of polarization, and by using a simulation tool based on Finite-Difference Time-Domain (FDTD) one can design a unique microstructure that enables to outcouple photons with a well-defined polarization state (Konishi *et al.*, 2011; Mrowiński *et al.*, 2016).

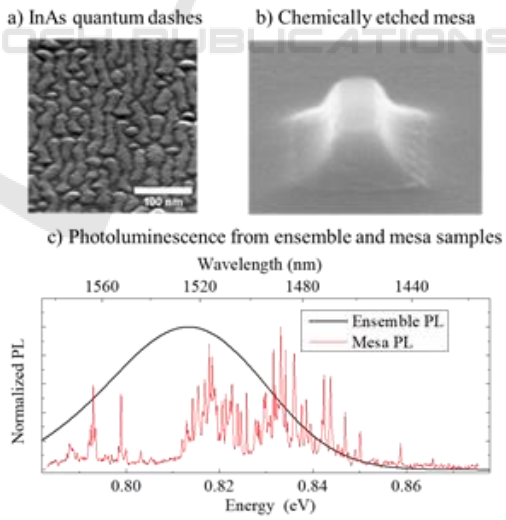

Figure 1: a) SEM image of uncapped InAs quantum dash sample b) chemically etched mesa of submicrometer in-plane size and 300 nm height c) photoluminescence spectra of both planar and processed samples showing isolated spectral lines for mesas due to limited number of optically active nanostructures.

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In this work, we focus on quantum dashes (QDashes) of the InAs/InGaAlAs material system grown on InP substrate by molecular beam epitaxy. The system consists of 200 nm barrier $In_{0.53}Ga_{0.23}Al_{0.24}As$ layer (lattice matched to InP), InAs 2-5 monolayers leading to nucleation of QDashes, 100 nm the same barrier and 10 nm InP. The QDashes are rather non-uniform nanostructures of high surface density of ~10^{10} cm^{-1} and elongated along [1-10] crystallographic direction reaching length of more than 50 nm (Sauerwald *et al.*, 2005; Reithmaier, Eisenstein and Forchel, 2007) (Fig. 1a). A spectral range of emission can be tuned from 1200 to 2000 nm by controlling the amount of nominally deposited InAs material, thus enabling their use in the active region of nanophotonic or optoelectronic devices devoted to operate at telecommunication windows of O-band (1310 $\pm$ 50 nm) and C-band (1550 $\pm$ 15 nm).

By using chemically etched submicrometer structures like asymmetric mesas shown in Fig 1b), the number of investigated nanostructures is limited to a few tens of optically active QDashes on 200 x 400 nm^2 area and 300 nm height. In Fig. 1 c) we demonstrated results of photoluminescence experiment performed on both ensemble and etched mesa structure showing well isolated spectral features for the mesa, which can be assigned to optical transitions from excitonic complexes confined in the QDash.

2 POLARIZATION ANISOTROPY OF QUANTUM DASH IN ASYMMETRIC MESA

In this section, we study the influence of mesa structure geometry on the polarization anisotropy of

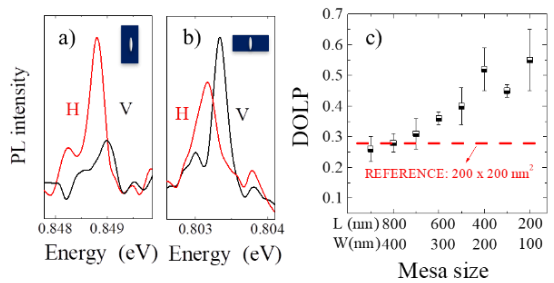

Figure 2: a) Polarization resolved emission of quantum dash exciton for rectangular mesa of 400 x 200 nm^2 oriented paralallel and b) perpendicular to the QDash axis showing DOLP of 0.5 and -0.2, respectively. c) A size dependence of DOLP measured for several excitons using fixed lateral aspect ratio.

excitonic emission around 1550 nm spectral range. All results can be quantified by a degree of linear polarization (DOLP) defined as $(I_H - I_V)/(I_H + I_V)$, where $I_{H(V)}$ is emission intensity from QDash polarized along [1-10] ([110]) in-plane directions.

First, we examined the reference sample, which is 200 x 200 nm^2 and we obtained a non-zero polarization anisotropy exciton line, which is typically in a range from 0.2 to 0.3 (Musiał, Podemski, *et al.*, 2012; Mrowiński *et al.*, 2016). Such noticeable anisotropy seen for QDashes results from the anisotropic quantum confinement due to the in-plane elongated geometry, which leads to a mixing in the valence-band and thus induces a difference in the oscillator strengths for the linearly polarized emission from mixed exciton bright states (Musiał, Kaczmarkiewicz, *et al.*, 2012; Tonin *et al.*, 2012; Singh, Kumar and Singh, 2017). Polarization anisotropy originated from the electronic structure is then an intrinsic contribution. Next, we performed similar measurements for asymmetric mesa structures, namely rectangular one of 400 x 200 nm^2 size, oriented both along the QDash elongation axis [1-10] and perpendicular to it. Such configurations results in DOLP of about 0.55 and -0.20, respectively (Fig. 2a,b). This effect has also been examined in function of the mesa size. In Fig. 2c) we present the measured DOLP of exciton emission for several mesas of fixed lateral aspect ratio of 2:1 oriented along QDash main axis and for increasing its base dimension up to 900 x 450 nm^2. It shows that the mesa influence on the DOLP decreases with the increasing size approaching 0.26 for the largest one, which is close to the value obtained for reference and in-plane symmetric mesa.

3 FDTD SIMULATIONS

We perform simple modelling using commercial-grade simulator (‘Lumerical Solutions, Inc.) based on FDTD to explain the experimental results concerning the polarization anisotropy. A spontaneous emission (SE) rate of exciton can be described in a dipole-approximation as $\Gamma = \frac{2\pi}{\hbar^2}\rho(\omega_{QD})\left|\vec{d}\cdot\vec{E}(r_{QD})\right|^2$, where $\rho(\omega_{QD})$ is local density of optical states, $\vec{d}$ is transition dipole moment and $\vec{E}(r_{QD})$ is electric field amplitude for the far-field mode at the position of the emitter. In the weak-coupling regime, the main contribution to the anisotropy is expected for the electric field, which is localized in the asymmetric mesa structures depending on its polarization. The

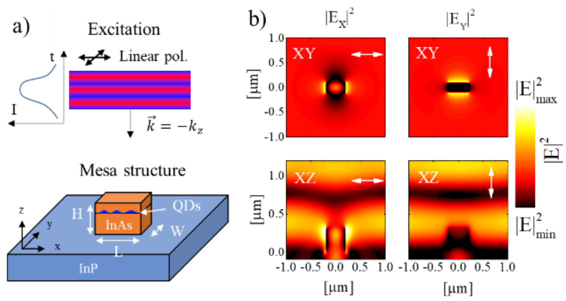

Figure 3: a) Simple model used for FDTD simulations of the optical field confinement inside the mesa structure for the far field modes. b) Simulation results of the polarized electric field intensity distributions using two representative projections for asymmetric mesa structure of 400 x 200 nm^2 and 300 nm height.

polarization degree of freedom is taken into account in the scalar product where the linearly polarized H(V) dipoles couples to the parallel component of the localized electric field.

We calculated the electric field intensity distribution inside a mesa structure using linearly polarized pulsed excitation normal to the sample surface, which is schematically shown in Fig. 3a). A spectral range is centred at 1550 nm. By using simplified geometry of InAs rectangular mesa on the InP substrate, we performed calculations for 400 x 200 nm^2 in-plane size and 300 nm height. In Fig. 3b) we demonstrate Fourier transformed results of polarized electric field distributions in a linear scale for both the in-plane projections and cross-sections along the longer mesa edge. We find that parallel configuration exhibits a noticeable localization of the field while cross-polarized case shows excluded field from the inside. By comparing the squared absolute amplitude values in the middle point of the mesa. We obtain about three times higher value for co-polarized component, which gives an optical DOLP defined as $(|E_H|^2 - |E_V|^2)/(|E_H|^2 + |E_V|^2)$ of 0.32. Such mesa induced polarization anisotropy influences the

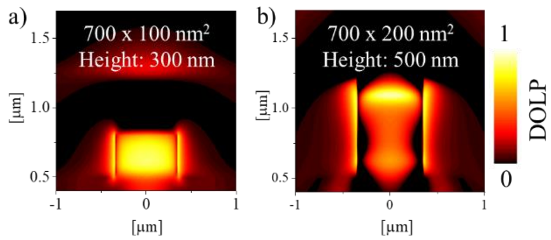

Figure 4: Optical DOLP calculated for mesa structures of high in-plane asymmetry and height of a) 300 nm and b) 500 nm showing qualitatively different distributions and maximum DOLP as high as 0.85.

emitter polarization and in the case of single QDash with intrinsic DOLP of 0.25 it results in anisotropy of SE rate on the level of 0.53 when the mesa is oriented parallel to QDash axis, or -0.08 when it is perpendicular to it. These results are in good agreement with the experimentally obtained DOLP for exciton emission for asymmetric mesa structures.

We can now use this modelling to find the limits of tailoring the polarization anisotropy of emission at 1550 nm wavelength by using asymmetric mesa structures of this kind. In Fig. 4 a) we demonstrate the calculated cross-sectional distribution of optical DOLP (mesa induced, i. e. for a symmetric quantum dot with no intrinsic DOLP) for mesa structure of 700 x 100 nm^2 in-plane size and 300 nm height. The distribution is rather uniform and optical DOLP is more than 0.85 inside the mesa. By exploiting a QDash as a quantum emitter embedded parallel in such a mesa structure, it would be possible to obtain anisotropy of SE rate above 0.9 due to additional intrinsic anisotropy of the emitter. In Fig. 4 b) we examined also mesa of 700 x 200 nm^2 and 500 nm height and we find a non-trivial distribution of optical DOLP showing the highest value of 0.9 at 50 nm below the top edge and lower than 0.6 in a lower region. Although high DOLP can be obtained in this configuration, it is crucial to control the position of QDash precisely along z-direction making fabrication procedure more problematic.

4 CONCLUSIONS

We demonstrated both experimental and numerical studies on developing highly linearly polarized emission from a single InAs quantum dashes emitting in the spectral range of the 3rd telecommunication window, i. e. at 1550 nm. We investigated anisotropic submicrometer mesa structures and we found their influence on a degree of linear polarization of exciton emission of about ± 0.3 by using parallel or perpendicular alignment with respect to the elongation axis of a quantum dash. Next, we presented simulations based on FDTD numerical modelling of polarized electric field intensity distributions inside a mesa structure, and thus we found a quantitative agreement with the experiment by calculating the polarization anisotropy of the spontaneous emission rates. Such methodology allowed proposing mesa structures of higher in-plane asymmetries to find conditions for the degree of linear polarization of more than 0.85 for a symmetric quantum dot or above 0.9 for quantum dashes.

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