Excitonic fine structure splitting in type-II quantum dots

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Excitonic fine structure splitting in quantum dots is closely related to the lateral shape of the wave functions. We have studied theoretically the fine structure splitting in InAs quantum dots with a type-II confinement imposed by a GaAsSb capping layer. We show that very small values of the fine structure splitting comparable with the natural linewidth of the excitonic transitions are achievable for realistic quantum dot morphologies despite the structural elongation and the piezoelectric field. For example, varying the capping layer thickness allows for a fine tuning of the splitting energy. The effect is explained by a strong sensitivity of the hole wave function to the morphology of the structure and a mutual compensation of the electron and hole anisotropies. The oscillator strength of the excitonic transitions in the studied quantum dots is comparable to those with a type-I confinement which makes the dots attractive for quantum communication technology as emitters of polarization-entangled photon pairs.

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I. INTRODUCTION

Excitonic fine structure splitting (FSS) refers to a tiny energy splitting of two bright exciton states confined in quantum dot (QD) heterostructures with a typical magnitude ranging from units to hundreds µeV. It is manifested in a doublet structure of the exciton recombination band. It was observed for the first time in GaAs/AlGaAs quantum wells with fluctuating thickness and then in various QD systems. Soon after its discovery it was attributed to the electron-hole exchange interaction and its finite value was related to the reduced symmetry, which needs to be lower than $D_{2h}$.

The interest in FSS is triggered by both fundamental and application point of view. FSS helps to distinguish the spectral features originating in the recombination of exciton (doublet), biexciton (doublet with opposite polarization-energy dependence), and trion (singlet). Benson’s proposal of the source of entangled photon pairs relying on zero FSS has called for the preparation of QD systems with low FSS. Using (111) substrates for the growth of InAs QDs reduced both structural asymmetry and piezoelectric contribution. Another attempt involved strain-free GaAs/AlGaAs QDs with zero piezoelectric field, which, however, still exhibited a finite FSS due to structural elongation. Post-growth annealing of InAs QDs allowed to decrease FSS from 96 µeV to mere 6 µeV. Another class of approaches is based on in-operation tuning, where the originally large value of FSS is reduced by applying the external field: electric, magnetic or strain. The external strain field allowed to reach FSS below experimental resolution in GaAs/AlGaAs QDs the simultaneous application of electric field allowed for a more powerful symmetry restoration and rather universal recovery of low FSS.

Various effects contributing to the FSS can be divided into two classes based on the involved length scale: atomic and macroscopic. Atomic-scale effects are connected with the irregularities of the crystal lattice such as the interfaces, particular elements distribution in alloys, charged defects etc. The magnitude of these effects is still subject of investigation; the atomistic simulations based on the tight-binding method predict considerably larger values than those relying on the empirical pseudopotential method. In general, atomic-scale effects are weak compared to those on macroscale. For example, the magnitudes of about 1 µeV are reported for a specific alloy distribution in the AlGaAs barrier of GaAs QDs. The effect is more pronounced when the dot material is an alloy, which should be therefore avoided when aiming at low FSS. A lower bound of several µeV was predicted for strain-tuned FSS in ternary In$_{0.6}$Ga$_{0.4}$As QDs. By macroscopic scale we mean for the purpose of the foregoing discussion that the characteristic length of the effect is comparable with the dimensions of a QD and the underlying crystal lattice is perceived as a homogeneous environment. Thus, the crystal symmetry is no longer relevant and the finite values of FSS are now related to the symmetry lower than $C_4$, i.e., to the lateral elongation of the wave functions (e.g.
envelope functions of the k-p theory). Principal contributions to the FSS on macroscopic scale arise from the asymmetric (elongated) shape of a QD and piezoelectric field. Further, it is possible to use the external strain field to induce the anisotropic effective mass tensor and modify the elongation of the hole wave functions and the related value of FSS.14

Further information is contained in the polarization properties of the exciton doublet. Simple considerations assuming a purely heavy-hole exciton in an elliptic-disk-shaped QD28 predicted a linear polarization of both transitions with the low-energy component polarized parallel with the long QD axis and the high-energy component having the orthogonal polarization. Typically, both structural-elongation and piezoelectric axes are parallel with the crystal axes [110] and [110], and so are the polarizations of both components. However, in some structures with shallow irregular confinement potential, such as quantum well thickness fluctuations, stochastic polarization directions were observed.29 Further, when the light-hole contribution to the exciton ground state becomes important, the polarization orthogonality of both components is lost.14,29

We focus here on QDs with type-II confinement, in which one type of charge carriers is confined in QD volume and the other in the barrier close to the QD vicinity. The particular system of interest are InAs QDs with a thin GaAs$_{1-y}$Sb$_y$ overlayer embedded in GaAs. One reason for selecting this material system is the possibility to induce a smooth crossover between type-I and type-II confinement regime simply by changing $y$; the crossover values between 0.14 and 0.18 have been reported.23,24 The other is that it belongs to the minority of systems with holes bound outside. Owing to their large effective mass the holes are more susceptible to the local potential profile or external perturbations, offering a larger potential for tuning their wave functions and the related FSS. The photoluminescence of GaAs$_{1-y}$Sb$_y$ capped QDs is rather intense despite the type-II confinement with the radiative lifetimes as low as 10 ns.25 The strain-reducing effect of GaAs$_{1-y}$Sb$_y$ layer together with the surfacing effect of antimony allow to increase the emission wavelengths of standard InAs QDs and reach the telecommunication wavelength of 1.3 and 1.55 μm.27,28 Various shapes of GaAs$_{1-y}$Sb$_y$ QDs have been reported, including a lens or a pyramid with a graded In concentration.29 Notably, the hole wave function is expected to be composed of two segments localized in the minima of the piezoelectric potential.24

In this work we present a theoretical study of excitonic fine structure splitting of InAs QDs with GaAs$_{1-y}$Sb$_y$ overlayer. We propose a method to tune the FSS by setting the thickness of the GaAs$_{1-y}$Sb$_y$ layer. The values comparable with the natural linewidth can be achieved even in low-symmetry QDs. The paper is organized as follows: In Section IV a theory of FSS is described. To gain a qualitative understanding of the relations between the wave functions and FSS we discuss in Section III a simplified single band model with Gaussian wave functions. The full calculations are presented in Section IV. We summarize and conclude in Section V.

II. THEORY

The single particle states were calculated within the eight-band k-p theory31,32 in which the wave functions are expanded into products of periodic parts of Bloch functions $u_b$ in the Γ point and corresponding envelope functions $\chi_b$:

$$\psi(r) = \sum_{b \in \{x,y,z,s\} \otimes \uparrow, \downarrow} u_b(r) \chi_b(r).$$

In this equation $b$ is the band index, the bands $x$, $y$, $z$ correspond to the valence band Bloch waves which are antisymmetric with respect to the corresponding mirror plane and $s$ corresponds to the conduction band Bloch wave. Following usual conventions, $z$ denotes the growth direction. The calculations include the effects of the elastic strain via the Pikus-Bir Hamiltonian33 and the piezoelectric field. The numeric simulations were performed with Nextnano 3D34 which employs the finite difference method. The simulation space was discretized with a step of 1 nm.

Once the single particle states are calculated, it is convenient to use them as a basis for the exciton state $|X\rangle$. First the Slater determinants $|X(ci, cj)\rangle = c_{ci}^\dagger c_{cj}^\dagger |0\rangle$ are formed, where $|0\rangle$ is Fermi vacuum state (empty quantum dot), $c_{ci}^\dagger$ creates an electron in $i$th conduction state and $c_{cj}$ annihilates an electron in $j$th valence state, the corresponding single-particle wave functions are denoted $\psi_{ci}$, $\psi_{cj}$, respectively. For the calculations of FSS we used four Slater determinants formed from the ground hole and electron states. Following Ref.3 (Eq. 2.3) the Hamiltonian matrix elements read

$$(E_i - E_j)\delta_{ij}\delta_{dl} + C(ci, cj, vk, vl) + EX(ci, cj, vk, vl)$$

where $E_i$ is the energy of $i$th single particle state, $C$ represents the direct Coulomb interaction, and $EX$ represents the exchange interaction.

Defining

$$S_{c,v}(r) = \sum_{b \in \{x,y,z,s\} \otimes \uparrow, \downarrow} \chi^*_{c,b}(r)\chi_{v,b}(r)$$

and vector $T$ with the components

$$T_{c,v}^\sigma(r) = \frac{P}{E_g} \sum_{\sigma \in \uparrow, \downarrow} [\chi^*_{c,\sigma}(r)\chi_{v,\sigma}(r) + \chi^*_{c,\overline{\sigma}}(r)\chi_{v,\overline{\sigma}}(r)]$$

and $T^\theta$, $T^z$ defined analogously ($E_g$ is the fundamental band gap and $P$ is one of the Kane’s parameter related to
the non-vanishing coordinate matrix elements \((x|x)s = P/E_s\), we can write

\[
C(c_1, v_1; c_2, v_2) = -\frac{e^2}{4\pi \varepsilon} \times \int dr_1 \int dr_2 \frac{1}{|r_1 - r_2|} S_{c_1, v_1}(r_1) S_{c_2, v_2}(r_2)
\]

\((e\) denotes the elementary charge and \(\varepsilon\) the dielectric function). The exchange Coulomb interaction term \(EX\) can be expressed as a sum of the following three terms:

\[
EX_0(c_1, v_1; c_2, v_2) = \frac{e^2}{4\pi \varepsilon} \times \int dr_1 \int dr_2 \frac{1}{|r_{12}|} S_{c_1, v_1}(r_1) S_{c_2, v_2}(r_2), \tag{2}
\]

\[
EX_1(c_1, v_1; c_2, v_2) = \frac{e^2}{4\pi \varepsilon} \int dr_1 \int dr_2 \frac{1}{|r_{12}|} \times r_{12} \cdot \left| S_{c_2, v_2}(r_2) T_{c_1, v_1}(r_1) - S_{c_1, v_1}(r_1) T_{c_2, v_2}(r_2) \right|, \tag{3}
\]

and

\[
EX_2(c_1, v_1; c_2, v_2) = \frac{e^2}{4\pi \varepsilon} \int dr_1 \int dr_2 \frac{1}{|r_{12}|} \times \sum_{\alpha, \beta \in x, y, z} T_{c_1, v_1}(r_1) T_{c_2, v_2}(r_2) [\delta_{\alpha \beta} |r_{12}|^2 - 3r_{12}^{\alpha \beta}], \tag{4}
\]

where \(r_{12} = r_1 - r_2\) and \(\delta_{\alpha \beta}\) is the Kronecker delta. We note that \(S\) is non-zero only when the mixing of valence and conduction bands is taken into account. Thus, only the third term of the multipole expansion, Eq. (3) contributes to the FSS when this mixing is neglected, e.g. when single band or six-band k.p theory is used to obtain the wave function of individual particles. However, as the scaling of the terms with the linear extension of the wave function \(L\) goes as \(EX_0 \sim 1/L, EX_1 \sim 1/L^2, EX_2 \sim 1/L^3\), the low-order terms are important in particular in larger QDs.

III. MODEL OF GAUSSIAN WAVE FUNCTIONS

Before treating realistic quantum dots with the full-complexity model, it is worth to provide an intuitive understanding of the relation between the topology of the excitonic wave function and the value of FSS. To this end we employed a simplified model with the exciton composed of a single Slater determinant, neglected band mixing, and the electron and hole densities having the form of three-dimensional Gaussian functions. The electron and hole envelope functions read

\[
\chi_{\alpha, \beta}(r) \propto \exp \left[ -\frac{(x-x_0)^2}{L_x^2} - \frac{(y-y_0)^2}{L_y^2} - \frac{(z-z_0)^2}{L_z^2} \right]^{1/2},
\]

where \(L_x, y, z\) determine the spatial extensions of the wave functions and \(x_0, y_0, z_0\) are the coordinates of the particle barycenter. As the band mixing is neglected, only the dipole-dipole exchange term (Eq. (4)) contributes to the total FSS.

A crucial parameter for FSS is the lateral elongation of the envelope functions defined as \(E_w = L_{x}/L_y\). It follows directly from Eq. (4) that for non-elongated envelope functions \((L_x = L_y)\) FSS acquires a zero value. The dependence of the FSS on the elongation is shown in Figure 1. In order to isolate the effect of the elongation and avoid unintentional variation of other parameters, we preserved the volume and the effective vertical aspect ratio of the model dots, i.e., values of \(L_z\) and the product \(L_x \times L_y\) were kept constant. First, we assumed the same envelope function for both electron and holes (orange and green line). Such case corresponds e.g. to strain-free GaAs/AlGaAs dots. FSS exhibits a monotonically increasing concave dependence on the lateral elongation \(E_w\). To demonstrate the effect of the QD volume, we show FSS for a smaller dot (extension parameters \(L_x \times L_y = 25 \text{ nm}^2\), \(L_z = 2 \text{ nm}\)) and a larger dot with two-times larger dimensions (e.g., eight-times larger volume). The values of FSS for a larger QD are exactly eight-times smaller. The inverse proportionality of FSS to the QD volume or to the third power of a characteristic linear dimension \(L\). 

FIG. 1: (color online) FSS as a function of the lateral elongation of the wave functions, defined as \(E_w = L_x/L_y\). A smaller dot with the extension parameters \(L_x \times L_y = 25 \text{ nm}^2\), \(L_z = 2 \text{ nm}\) is shown by the orange line. A smaller dot with the extensions twice larger than for the smaller dot, i.e., \(L_x \times L_y = 100 \text{ nm}^2\), \(L_z = 4 \text{ nm}\) (magenta line) A smaller dot, \(L_x \times L_y = 25 \text{ nm}^2\), \(L_z = 2 \text{ nm}\), with opposite electron and hole elongation. For electrons, \(E_w\) has a constant value of 2/3. For holes, \(E_w\) is varied and FSS is displayed as a function of the hole elongation. (insets) The insets schematically depict the topology of the wave functions. Hatched magenta ellipses correspond to the electron wave functions.
can be directly inferred from Eq. 4. With the band mixing taken into account, additional terms proportional to $1/L$ and $1/L^2$ emerge. However, the $1/L^3$ or $1/V$ scaling law ($V$ representing a volume of the QD) has been recently demonstrated experimentally in realistic strain-free GaAs/AlGaAs QDs. FSS values exceed the natural linewidth of the exciton recombination lines (up to units of $\mu$eV) even for a modest elongation. For example, for $E_w = 1.2$ we predict FSS of 11 $\mu$eV (1.4 $\mu$eV) in the smaller (larger) QD. We note that for the QDs studied in Ref. 37 we found the values of $L_x \times L_y$ between 11 and 36 nm$^2$ and $L_z$ between 1 and 2 nm. The smaller dot case thus corresponds well to realistic GaAs/AlGaAS QDs.

Next, we introduce an important concept of the compensated elongation. For a suitable exciton wave function topology, FSS can attain the zero value even in the system that lacks the required symmetry $C_{2v}$. We consider the electron envelope function to be elongated in the direction perpendicular to the elongation of the hole envelope function, $E_{we} = 2/3$ (the subscripts $e$, $h$ are used, when required, to distinguish the parameters of electrons and holes, respectively). The extension parameters correspond to the smaller dot: $L_x \times L_y = 25$ nm$^2$, $L_z = 2$ nm. FSS is plot as a function of the hole elongation $E_{wh} \geq 1$ in Fig. 1 (magenta line). The prominent feature of the dependence is the zero-value minimum at $E_{wh} = 3/2$, (i.e., the inverse of the hole elongation. Intuitively, this can be described as the mutual compensation of both electron and hole elongations. The integral in Eq. 4 attains a zero value, which is however not related to the symmetry. In realistic QDs, the condition of the inverse elongation does not hold (due to band mixing or different volume of the envelope function of electrons and holes) but the effect is preserved. The minimum value of FSS can be larger than zero in case of QDs with the irregular shape. The effect of the compensated elongation has been already demonstrated experimentally utilizing the anisotropic external strain to vary the elongation of the hole envelope function. In the following we will demonstrate that the elongation of the hole envelope function can be efficiently varied in type-II InAs QDs with GaAsSb capping layer.

The transition between type-I and type-II confinement in GaAs$_{1-x}$Sb$_x$ capped QDs is accompanied by the splitting of the hole wave function into two segments, evenly spread along the central electron wave function in QDs with a sufficient symmetry (Fig. 2b,c). The behavior of FSS under such transition is shown in Fig. 2. When the connecting line of the segments is parallel to the elongation axis (orange line), small segment shifts from the central position effectively enhance the hole elongation and consequently the FSS. For larger shifts the wave function disintegrates; now the effect of increased distance of electron and hole prevails resulting into a decrease of FSS. The same behavior is predicted for non-elongated wave functions (green line), where the FSS dependence starts at a zero value, increases as the holes become effectively elongated, and decreases when the separation effects prevail. When the connecting line of the segments and the elongation axis are perpendicular, the effective elongation of the holes decreases as the segments are separated, and so happens with FSS. Depending on the magnitude of the original elongation, two possibilities exist: (1) The hole eventually becomes elongated in opposite direction (magenta line; note the magenta insets of Fig. 2 schematically depicting the change in the elongation direction). FSS goes through a zero value and starts to increase again. Finally, the separation effects prevail and FSS decreases. (2) When the original elongation is large, the hole disintegrates before the elongation direction is changed (maroon line). In such case a monotonously decreasing dependence of FSS on the segment distance is observed, governed first by the decrease of the effective elongation and then by the separation effects.

In strongly asymmetric QDs the minima in confinement potential corresponding to both segments can differ considerably and a single-segment hole wave function displaced from the central electron wave function can be formed. In such case there is no effective change in the elongation and the separation effect leads to a monotonous decrease of FSS as in the case of large perpendicular elongation (not shown).
IV. REALISTIC QUANTUM DOTS

We will now focus on realistic InAs QDs with a GaAs$_{1-y}$Sb$_y$ capping layer. We will show that FSS in such structures can be tuned by the thickness of the GaAs$_{1-y}$Sb$_y$ layer, allowing its decrease below the natural linewidth of the exciton transitions.

To show the universality of the tuning approach, three QD geometries will be considered here, denoted as pyramidal, symmetric lens-shaped, and elongated lens-shaped. The pyramidal QD is adopted from Ref. 30 and has the shape of a pyramid with the base length of 22 nm, height of 8 nm, and the trumpet indium composition profile within the pyramid. For the other structures we assume QDs composed of pure InAs. The symmetric lens-shaped QD is modeled as a top of a sphere with the base radius of 8 nm and the height of 4 nm. The prominent cause of the lateral asymmetry and contributor to FSS of many QD systems is a structural elongation. So far no elongation was reported for InAs QDs with GaAs$_{1-y}$Sb$_y$ overlayer, which is in striking contrast with InAs QDs capped by pure GaAs. This can be attributed to the surfacing effect of antimony but it is also possible that the elongation has been overlooked as the methods involved in experimental studies were insensitive to it. Therefore, we consider in our study also the possibility that QDs are elongated. In accordance with GaAs capped InAs QDs we select the direction $[110]$ as the main elongation axis and quantify the elongation by the ratio of characteristic lateral dimensions along $[110]$ and $[110]$, denoted as $E_s$ in the following (the subscript $s$ is used to differentiate the structural elongation from the wave-function elongation used in the previous section). The elongated lens-shaped QDs are formed from the lens-shaped dot by its stretching along $[110]$ and compressing along $[110]$ by the same factor so that the QD volume and height are preserved. All QDs are capped with the GaAs$_{0.8}$Sb$_{0.2}$ layer of a certain thickness and further embedded in GaAs.

The topology of the wave functions is closely connected with the effective confinement potential, which is contributed by the band-edge offsets, strain field, and piezoelectric potential. We construct the potential without the piezoelectric contribution from the eigenvalues of the pointwise diagonalized Hamiltonian (terms containing the spatial derivatives are discarded and the Hamiltonian is then diagonalized at each point of the simulation grid) so the strain-induced band mixing is already involved. The hole potentials in all type-II QDs discussed further in the paper exhibit qualitatively similar features. We will present them for the exemplar lens-shaped QD with the GaAsSb layer thickness of 5 nm and with the elongation $E_s$ of either 1 or 2. Figure 3 shows the potential profile without the piezoelectric contribution. The potential is given from the electron view, the largest values correspond to the minima of the hole confinement. Zero energy is set to the valence band edge of bulk unstrained InAs. Two local minima of the hole confinement potential are formed in the GaAsSb layer along the sides of the QD and above its top [Fig. 3(a)]. The top-minimum is of the light-hole character and therefore penalized by the quantum confinement. The ground hole state will be localized in the side-minimum which forms a ring around the QD [Fig. 3(b)], in which weak variations of the potential are present with two rather shallow absolute minima along the long QD side (i.e., in $[110]$ direction from the QD center). Depending on the magnitude of these variations, the wave function might form a ring or be split into two segments.

The piezoelectric field has an octopole shape shown in Figure 2. Its contribution is rather important as its magnitude of about 50 meV is comparable to the variations of the rest of the confinement potential inside the GaAs$_{1-y}$Sb$_y$ layer. The horizontal nodal plane of the piezoelectric octopole lies close to the side-minimum of the confinement potential. The piezoelectric potential therefore tends to split the wave function of the holes in the side-minimum into two segments situated along $[110]$ below the nodal plane or along $[110]$ above the nodal plane.

The total confinement potential is shown in Figure 3. The following morphologies of the hole wave function are
possible: (i) inside a QD (type I), (ii) a ring-like shape along the QD when the piezoelectric field is too weak to localize the holes in its minima, (iii) two segments at the dot base situated along [110] [Fig. 6(a),c)], (iv) two segments at the QD sides above the piezoelectric nodal plane situated along [110] due to the piezoelectric field [Fig. 6(b)] or along [100] when the structural elongation along [110] prevails [Fig. 6(d)] is close to that case. In pyramidal QDs with the trumpet In composition profile, both the side-minimum of the confinement potential and the piezoelectric octopole are shifted up towards the region of large In content. In short, there is a rich variety of the hole wave function morphologies. Variation of the parameters such as the thickness or the composition of the GaAsSb layer are supposed to induce transitions between those morphologies. For example, switching between the deep narrow minima below the nodal plane [Fig. 6(a),c)] and shallow broad minima above the nodal plane [Fig. 6(b),d)] shall be achievable. Considering the effect of the compensated elongation, this opens an interesting prospect for the tuning of FSS.

Figure 6(d) shows the dependence of FSS on the thickness of the GaAs$_{1-x}$Sb$_x$ layer in two lens-shaped QDs: symmetric and weakly elongated ($E_s = 1.1$). We will first discuss the case of the symmetric QD. The electron wave function is weakly elongated in [110] direction and as it resides within the QD, its variation with the thickness of the GaAs$_{1-x}$Sb$_x$ layer is negligible. For a thin GaAs$_{1-x}$Sb$_x$ layer (up to 3 nm) the ground hole wave function resides inside the QD, too. It experiences the bottom part of the piezoelectric octopole and is thus elongated in [110], as shown in Fig. 6(a). The polarization of the lower exciton component is [110]. With increasing thickness a hole ground state gradually shifts into the GaAs$_{1-x}$Sb$_x$ layer and also slightly upwards (for about 1.3 nm for the full range of thicknesses). Consequently, it becomes split by the upper part of the piezoelectric octopole into two segments along [110]. For the thickness interval between 3 and 5 nm, the segmented wave function behaves as effectively elongated in [110] [Fig. 6(b)] and the lower exciton component is also polarized along [110]. For the thickness values above 5 nm, the segments are well separated and the elongation of each segment in [110] determines the overall symmetry of the wave function. The lower exciton component is again polarized along [110]. Thus, we distinguish three regions of different exciton polarization. At each of the two transitions between those regions, exciton levels cross and FSS is reduced to zero. We note that minimum values obtained in our calculations are non-zero due to the finite
step in the thickness dependence and read 0.1μeV and 1μeV for the first and second transition, respectively. The observed behavior of FSS corresponds well to the qualitative prediction of the model of Gaussian function for $L_x/L_y = 5/6$ (cmp. Fig. 2 magenta line).

Similar behavior is observed in a lens-shaped QD weakly elongated in [110] [Figure 3(d), green lines]. The first region is now missing, as the elongation of the hole wave function within the QD volume (for a thin GaAs$_{1-y}$Sb$_y$ layer) is now [110] because the structural elongation dominates over the piezoelectric contribution. The zero FSS is reached for a GaAs$_{1-y}$Sb$_y$ layer thickness of 7 nm. Figure 7 shows the FSS dependence on the thickness of the SRL layer in a pyramidal QD with the lens-shaped QD, 0.10 for the elongated lens-shaped QD, and 0.12 for the pyramidal QD. Thus, roughly 5-times weaker photoluminescence as compared to type-I QDs is expected. For this reason we are convinced that the extraction of individual photons or photon pairs from individual GaAs$_{1-y}$Sb$_y$ capped QDs will be experimentally feasible.

V. CONCLUSIONS

In GaAs$_{1-y}$Sb$_y$ capped InAs QDs, lateral symmetry of the hole wave functions can be to a large extent influenced by the thickness of the GaAs$_{1-y}$Sb$_y$ layer. In particular, during the crossover between type-I and type-II confinement regimes, the hole wave function is shifted upwards across the nodal plane of the piezoelectric octopole, which is accompanied by the change of the direction of lateral elongation. Due to the mechanism of compensated elongation, a crossing of the bright exciton levels and a reduction of FSS to zero is predicted for certain thicknesses of the GaAs$_{1-y}$Sb$_y$ layer. Low natural FSS and efficient photoluminescence make the GaAs$_{1-y}$Sb$_y$ capped InAs QDs attractive as a possible source of entangled photon pairs.

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