Reviewing quantum dots for single-photon emission at 1.55 µm: a quantitative comparison of materials

L Seravalli1 and F Sacconi2

1 CNR-IMEM Institute, Parco delle Scienze 37a-I, 43100, Parma, Italy
2 Tiberlab Srl, Via del Politecnico, 1, 00133, Roma, Italy

E-mail: luca.seravalli@imem.cnr.it

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Abstract

In this work, we present a review of quantum dot (QD) material systems that allow us to obtain light emission in the telecom C-band at 1.55 µm. These epitaxial semiconductor nanostructures are of great technological interest for the development of devices for the generation of on-demand quanta of light for long-haul communication applications. The material systems considered are InAs QDs grown on InP, metamorphic InAs/InGaAs QDs grown on GaAs, InAs/GaSb QDs grown on Si, and InAsN QDs grown on GaAs.

In order to provide a quantitative comparison of the different material systems, we carried out numerical simulations based on envelope function approximation to calculate the strain-dependant energy band profiles and the associated confined energy levels. We have also derived the eigenfunctions and the optical matrix elements for confined states of the systems.

From the results of the simulations, some general conclusions on the strengths and weaknesses of each QD material system have been drawn, along with useful indications for the optimization of structural engineering aiming at single-photon emission in the telecom C-band.

1. Introduction

The generation and manipulation of single photons is a keystone for the development of quantum photonics devices [1–3]. In particular, for quantum-safe long-haul communication systems, reliable on-demand sources of quantum light in the telecommunication C-band at 1.55 µm are urgently needed [4].

Epitaxial self-assembled quantum dots (QDs) can be considered as the most investigated semiconductor nanostructures for the generation of quantum light and, after convincing success in the generation of quantum light in the 1.0 µm range [1, 5, 6], research efforts have been recently focused on obtaining quantum photonic sources in the telecom range.

One of the weaknesses of QDs is related to the low temperature of operation for single-photon emission, due to a reduction of the emission coherence, caused by phonon-related linewidth broadening. Other structures such as carbon nanotubes (CNTs) and GaN nanostructures have been demonstrated to be able to emit single photons up to room temperature. However, only As-based QDs have purities in excess of 99% with high brightness of emitted light, whereas CNTs suffer from low brightness and poor stability [3], while GaN structures are incapable of emitting light in the infrared region, as they are limited to the 280–600 nm range [7]. Moreover, epitaxial QDs provide various advantages for the development of single-photon devices, such as the possibility to control position during growth and their easy integrability with optical cavities or advanced photonic structures for enhancement and control of emitted quantum light.

Different QD material systems have been proposed to achieve single-photon emission in the C-band with very encouraging results: (i) metamorphic InAs/InGaAs grown on GaAs [8], (ii) InAs/InGaAlAs grown on InP substrates [9–11], and (iii) InAs/GaAssb grown on silicon [12].

As the amount of research on this topic is currently increasing, at this stage it can be useful to compare different QD material systems from a theoretical point of view, to ascertain the peculiarities, the intrinsic...
advantages and the disadvantages of specific systems. This in-depth knowledge will concur with other
elements to achieve a complete assessment of the possible different options available; many other criteria
should be considered when choosing a material system: growth requirements, fabrication technology, costs
and technology transfer considerations.

Nevertheless, a review of the general theoretical scenario of available material systems is indeed useful to
understand what performances can be expected, in particular from the point of view of single-photon
emission.

To this aim, we performed numerical simulations by means of the simulation software tool TiberCAD
[13], to calculate an energy system for QD structures that can give 1.55 µm emission at 10 K and derive some
relevant figures for single-photon emission:

• Intrinsic spontaneous power density, determined by the oscillation strength, that gives an indication of the
  emission intensity from QDs.
• Confined ground and excited levels for electrons and holes: the energy level system has relevant effects for
carrier kinetics (due to thermalization processes) and for optical pumping (resonant or quasi-resonant).
• Energy distance between QD levels and states that can act as channels for thermal escape of carriers (wetting
  layers—WLs or confining layers—CLs): this a fundamental parameter for light emission at temperatures
higher than 10 K. As evidenced in the literature [14, 15], under low excitation levels, this energy barrier
(given by the total barrier heights for electrons and holes) corresponds to the activation energy for thermal
quenching of the emission. It should be noted that this is valid for QD ensemble emission: it has been very
recently discussed how, for a single QD, this barrier energy might correspond to the separation of single-
particle confined levels [16].
• Localization of carrier wavefunctions and type of quantum confinement (type I or type II), that has a direct
effect on exciton and multi-exciton binding energy.

Although the calculation of fine structure splitting (FSS) goes beyond the scope of this work, we will
report values from the available literature to give some indications on the possibility of having entangled
photon emission from the different materials considered here.

2. TiberCAD simulation tool

In this study, we used the TiberCAD multi-scale simulation tool, which has proved effective in the numerical
study of several semiconductor low-dimensional nanostructures [13, 17–19]. TiberCAD offers a modeling
environment where several different physical models may be coupled in an integrated simulation, even on
different scales, ranging from continuous to atomistic level. Analysis and optimization of electronic and
optoelectronic devices may be performed at all the relevant length scales, including linking and
self-consistent coupling of different models. Continuous models based on the finite element method, such as
drift-diffusion transport, the k · p multiband quantum electronic model, heat flow, strain and
piezoelectricity may be combined with atomistic methods, such as empirical tight binding, applied on
material structures generated in user-defined device regions.

3. Numerical methods

A QD system is generally composed of a nanometer region of a lower-gap semiconductor surrounded by a
larger-gap material: this confining potential causes the confinement of electrons and holes in the conduction
and valence band, respectively. As the confining potential is effective along all three spatial dimensions, the
quantum confinement results in atomic-like discrete energy levels. Consequently, optical transitions between
single confined carriers yield single-photon emission. A calculation of emission energy, therefore, depends
on quantum energy levels and essentially consists of solving the Schrödinger equation for electrons and holes
in the conduction and valence bands: the energy levels and carrier wavefunctions depend on system
parameters such as material compositions, QD size and shape, and strain effects due to lattice mismatch.

In TiberCAD, the calculation of lattice mismatch-induced strain is based on the linear elasticity theory of
solids [20], assuming pseudomorphic interfaces between different materials. This approach is
computationally favorable and allows results to be easily included in a k · p–model [21].

Thus, in our simulations, firstly the strain and deformation fields due to the lattice materials are found
through minimization of the elastic energy, then the conduction and valence band edges, along with the
effective masses, are obtained from bulk k · p calculations, including the local corrections due to strain.
Strain-dependent energy bands for all materials of the quantum system are then calculated by solving the
Poisson equation for the system at equilibrium.
Finally, the Hamiltonian of the system is built following the eight-band $k \cdot p$ theory \cite{21} in the framework of the envelope function approximation. By solving the eigenvalue problems resulting from this model we obtain the energy spectrum, that is eigenenergies and eigenfunctions of the system, and the optical matrix elements. Further information on the calculations of these systems with TiberCAD can also be found in \cite{22}.

For each studied QD system, we designed a 3D model of a single undoped QD alongside its associated WL; data on QD composition, size and shape were taken from literature reports and details are given in the sections dedicated to each specific material system.

We must stress the relevance of particular material parameters such as the band offset between QD and CL materials, which were found to have a strong influence on the confining potential. In this work, the best available data in the literature have been considered, taking into consideration also the bowing effect in the case of alloys \cite{23}. Similarly, QD properties such as the size, shape and composition have an important impact on the results. For this reason, uncertainties in the precision of these values determine the range of confidence of the model calculated results; it has been shown in previous publications \cite{22} that, for the case of metamorphic InAs/InGaAs QDs, the range of variation of values can be set at $\pm$ 20 meV.

As output values of the simulation, we considered (i) strain-dependent energy band values, (ii) eigenenergies for the confined levels for electrons and holes, (iii) 3D probability densities for calculated states, as derived from eigenfunctions, and (iv) the optical spectrum of spontaneous power density for optical transitions in the 0.75–0.90 eV range (1.65–1.38 $\mu$m) at 10 K, coming from the calculation of the dipole matrix elements for the energy states. As the calculation of the emitted power does not take into consideration external parameters such as non-radiative recombination mechanisms and carrier pumping processes, it should be considered as a semi-qualitative indication to compare only the effects due to different oscillation strengths in different material systems.

The calculated QD systems are those reported as able to emit at 1.55 $\mu$m at 10 K: (i) metamorphic InAs/InGaAs QDs grown on GaAs, (ii) InAs QDs grown on InP substrates, (iii) InAs/GaSb QDs grown on GaAs, and (iv) InAsN/GaAs QDs grown on GaAs. It is worth mentioning that in all the above cases, single-photon emission has been demonstrated in recent years, except for the diluted nitride InAs QDs where issues related to material quality have hampered this achievement.

For each system, we will present the main results of the calculation in a figure that summarizes the essential features, while at the end of the paper we have included a table to give a quantitative general picture of the different system parameters.

4. Results and discussion

4.1. InP-based QDs

QDs grown on InP have historically been the most studied ones for emission at 1.55 $\mu$m, due to the favorable strain situation that allows a lower energy gap for QDs, compared to GaAs-based QDs. Indeed, single-photon emission from such QDs has been demonstrated since 2007 \cite{11, 24} and InP-based QDs have been shown to have an intrinsic FSS lower by an order of magnitude than their Ga-As-based counterparts \cite{25}. In addition, InP is the substrate of choice for commercial telecom lasers; therefore the technological transfer towards mass production of single-photon devices based on this material is expected to be viable.

Many works have been published in recent years with various QD designs and features. As the aim of this work is to give a general scenario of different QD systems, we have chosen to simulate two structures that can be considered as archetypical for this material system: (A) the basic InAs/InP one, consisting of an InAs QD of truncated conical shape with a ratio between lower and upper diameters equal to 3; the QD has a diameter of 20 nm and a height of 4 nm and it is embedded in InP layers, following the results of \cite{26} and \cite{25}; (B) a more complex design that considers an In$_{0.33}$Ga$_{0.67}$As$_{0.24}$ layer (lattice-matched to InP) embedding larger In$_{0.8}$Ga$_{0.1}$As QDs having diameters of 22 nm and heights of 12 nm, as described in \cite{27}. It is important to note that in this case the shape is more conical with a smaller upper diameter of 2 nm.

It is clear that the calculated properties are given as an indication of the range that can be covered, as other InP-based QDs could have different values of relevant parameters. Nevertheless, it still seems useful to have a general overview of the figures-of-merit for this system, in particular as a benchmark for less studied material systems.

The results of our simulations agree with reports that indicate that both types of structures can emit in the C-window, but the consistent differences in QD morphology and composition have an impact on the properties of the quantum energy system. In particular, for the InAs/InP system a photoluminescence (PL) peak emission around 0.780 eV at low temperature was measured \cite{26}, agreeing with an expected value of 0.806 eV based on the result of the simulations. For the system in case B the calculated ground levels for electrons and heavy holes determine an emission energy of 0.808 eV, in substantial agreement with a PL experimental value in the range of 0.820 eV \cite{27}.
As shown in figures 1 and 2, both structures allow emission in the 1.55 μm range, although the larger QDs have a slightly lower oscillation strength, possibly due to the smaller overlap between electron and hole wavefunctions.

The very different band alignment shown in figures 1(a) and 2(a) has a direct effect on the confined energy level configuration: in case of smaller InAs/InP QDs, ground states are well separated from excited states (by 57 meV for electrons and by 26 meV for holes), while in the larger InAlGaAs QD this energy separation is reduced to 17 meV for electrons and 4 meV for holes.

The different configurations of these quantum systems affect some physical processes that involve confined carriers: on one hand, photogenerated carriers have different paths to relax from CL states to confined QD levels, and on the other, closer energy levels might allow direct generation of photocarriers in the excited levels.

Such differences in the physics of the quantum systems could result in very different performances of single-photon devices from the point of view of (i) device dynamics due to different thermalization processes that can influence carrier kinetics [28], (ii) quasi-resonant and non-resonant pumping configurations, and (iii) separation of exciton and multi-excitons coming from different confined states. As can be observed in

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**Figure 1.** Model results for an InAs/InP QD: (a) valence band (red line) and conduction band (blue line) profiles along growth direction—energies of three confined levels are indicated as blue (electron ground state), light blue (first excited electron level), cyan (second excited electron level), red (heavy hole ground state), light red (first heavy hole excited level), and purple (second excited hole level) dashed lines; (b) spectrum of spontaneous power density for confined electron-heavy hole transition as function of energy with indications of emission from QD ground states (QD₀) and QD excited states (QD₁, QD₂); (c) calculated probability density for confined electrons for ground state; (d) calculated probability density for confined heavy holes for ground state.
Figure 2. Model results for an InGaAlAs/InP QD: (a) valence band (red line) and conduction band (blue line) profiles along growth direction—energies of three confined levels are indicated as blue (electron ground state), light blue (first excited electron level), cyan (second excited electron level); dashed lines; purple (heavy hole ground state), light red (first heavy hole excited level), and purple (second excited hole level) dashed lines; (b) spectrum of spontaneous power density for confined electron-heavy hole transition as function of energy with indications of emission from QD ground states (QD$_0$) and QD excited states (QD$_1$, QD$_2$); (c) calculated probability density for confined electrons for ground state; (d) calculated probability density for confined heavy holes for ground state.

The expected optical spectrum is rather different, aside from the QD$_0$ line: for smaller QDs the emission from excited states is much more distant from that from ground states. The last point concerns the distance in energy from confined ground states to WL states that are known to be the most effective escaping channel for thermally activated carriers: the calculation of WL states for the two structures resulted in a WL level at 1.146 eV for case A and at 1.044 eV for case B. These values agree well with the reported experimental PL emission energy for the two systems: 1.160 eV for case A [26] and 1.030 eV for case B [29].

This means that the energy separation for small InAs/InP QDs is 312 meV while it is 214 meV for larger InAlGaAs QDs, with considerable effects on the thermal quenching of emission.

This is true also in the case of considering the energy separation between confined levels as the effective energy barrier for emission quenching of single QDs, as there is a larger shell spacing for smaller InAs/InP QDs.

It should be noted that InAs/InAlGaAs/InP quantum dashes (that are rather elongated nanostructures) have recently been shown to emit single-photon emission up to 80 K [10]; our results suggest that for further increasing the operating temperature a configuration with higher band discontinuities would be advisable.
4.2. Metamorphic InAs/InGaAs QDs

InAs QDs grown on metamorphic InGaAs buffers have been studied for almost 15 years as a useful design to redshift the QD emission towards 1.3–1.55 µm for structures grown on GaAs substrates [30–32]: this is obtained thanks to the reduced mismatch between QDs and CLs [35, 34].

More recently, the use of InAs QDs grown on metamorphic InGaAs buffers has gained considerable interest for the development of single-photon sources in the C-band with considerable success [8, 9, 16, 35]. A dedicated review was published very recently, discussing how this design is very valuable from a technological point of view, thanks to the use of a GaAs substrate, and how single and entangled photons can be obtained [36].

Indeed, there is a technological push towards the use of this material rather than InP, as substrates of the latter material are more expensive and provide inferior heat sinking to GaAs ones. Moreover, growth on GaAs allows for the fabrication of AlAs/GaAs Bragg stacks needed for devices with vertical cavities emitting photons from the surface. This is not easily achievable with InP, as a lattice-matched material with the required refractive index difference is lacking [37].

Moreover, in-depth studies of electrical properties of metamorphic QDs concluded that the defect density in these strain-relaxed nanostructures is comparable to that of standard InAs/GaAs QDs, thus making the fabrication of devices with good performance feasible [38, 39].

In this work, we considered a metamorphic QD structure engineered for emission at 1.55 µm at 10 K as derived by a previous study [22] that considers an InxGa1−xAs metamorphic buffer with x = 0.50, an InyGa1−yAs QD with y = 0.75 and an InzGa1−zAs upper CL with z = 0.55. The QD has a truncated conical shape with d = 20 nm and h = 7 nm: such values were extracted by experimental data published previously: agreement between calculated values of QD emission and PL emission provided a confident validation of the model [40, 41].

An important feature to note is that in these nanostructures the degree of confinement is considerably low, up to the point of having electrons or heavy holes not confined in the QD, leading to type-II quantum-confined systems [22]. This change of the nature of the physical quantum system has a direct effect on the physics of confined carriers and on their recombination properties, as a weak confinement affects the probability of radiative recombination and, hence, the emission efficiency of quantum light. In addition, smaller confinement energies result in a lower population of ground states when the temperature is increased. This feature can have an impact if single-photon operation at higher temperatures is required, in particular for a large population of ground levels.

The results of the calculations yield a value of emission energy of electron-heavy hole recombination from ground states of 0.806 eV; this value is within the confidence interval of 20 meV with reported PL emission from metamorphic QDs of 0.810 eV [16].

In figure 3 the results of the simulation are presented. The most noticeable features (figure 3(a)) are the very low band discontinuities between QDs and InGaAs CLs, that result in a very small confinement, in particular for heavy holes. Indeed, only two confined states for electrons and holes were found when solving the eigenvalue equation and, hence, the simulated optical spectrum of figure 1(b) consists of one strong QD0 emission line, while the emission from excited states (QD1) is almost totally covered by the emission from states in the InGaAs CLs.

To highlight the fact that in this system the control of composition is of paramount importance, we carried out a simulation where the value of upper CL in concentration y was increased to 0.60: the result was that the electron was no longer confined in the QD, resulting in a type-II quantum system. See supporting information (available online at stacks.iop.org/JPMATER/3/042005/mmedia) for values of calculated probability densities. This result confirms the indications of [22] where it was concluded that with x = 0.50, the values of y at which a type-I system could be obtained are limited to 0.60 > y > 0.40.

It has been previously discussed that in metamorphic QDs with high x the WL state might not be present [42, 43]; therefore, in this particular case, there are reasons to identify the higher-energy levels, where thermally activated carriers might escape, with the InyGa1−yAs CL states. As a matter of fact the present calculation shows that the second excited states for electrons and holes are located mostly in the capping layer, as shown in the supporting information.

The value of the calculated energy gap of In0.55Ga0.45As, equal to 0.825 eV, is confirmed by an experimental value of PL emission energy of 0.837 eV reported in [44]. Moreover, it should be mentioned that WL calculations carried out with the same model for lower compositions of In in CLs were validated by similar PL characterization data [45].

Another important consequence of the low degree of confinement is that the energy distance between ground QD states and CL levels is 19.3 meV, a value that makes the thermal escape of confined carriers a very strongly competing process with radiative recombination when temperatures are raised. For this reason, for
higher-temperature operations, advanced designs for increasing carrier confinement are needed, such as the use of InAl(Ga)As barriers [41].

It should be noted that very recently single-photon emission at 77 K from metamorphic QDs was reported [16]: it was argued that the activation energy for a single QD corresponds to the shell spacing, thus resulting in much lower values than for the ensemble. For a QD ensemble the activation energy for thermal escape of confined carriers is determined by the energy difference between QD ground levels and states that can act as escaping channels (WL or CL). This energy barrier is given by the sum of the energy differences for electrons and heavy holes.

From the point of view of emission efficiency, the oscillation strength for the ground state is very similar to the InP-based QDs, making these structures an attractive design for low-T single-photon emission, thanks to the technological advantage of being grown on GaAs substrates; for example, it is possible to fabricate lattice-matched distributed Bragg reflectors based on high refractive index contrast materials such as AlAs and GaAs.

The presence of higher energy levels at 12 meV for electrons and 4 meV for holes also allows for the use of quasi-resonant optical pumping schemes.

4.3. InAs-GaSb QDs
The method of capping InAs QDs with GaSb layers to redshift their emission towards the telecom C-window has been known for some years, and the results are convincing [46, 47]. The peculiar band alignment results
in type-II confinement of carriers: thus, a strongly reduced emission efficiency might have discouraged research into the possibility of having quantum light from such nanostructures. However, recently, single QD emission from InAs/GaSb nanostructures grown on silicon was observed, a first step towards the realization of single-photon sources based on this material system [12]. Therefore, despite the expected reduction of recombination efficiency due to the spatial separation between confined electrons and holes, we included InAs/GaSb QDs in this overview of material systems for single-photon sources.

For this calculation we relied on the parameters provided in [12], with the QD having a truncated conical shape with a ratio of 3 between diameters. Base diameters of 23 nm are reported. It is known that the GaAsSb cap layer usually has a non-uniform composition and that the vertical InAs profile is not easy to determine accurately, making the values of QD heights and composition somewhat arbitrary [12, 48]. As these calculations should be considered as a tool to indicate general properties and provide guidelines, we considered a height value of 8 nm and QD consisting of In_{0.90}Ga_{0.10}As alloy (considered as an average value from published experimental data) as such values resulted in QD emission at 1.55 µm. The cap layer was 6 nm thick and composed of GaAs_{0.74}Sb_{0.26}, in agreement with [12].

The results of the calculation predict an emission energy from ground state recombination at a low temperature of 0.792 eV, while the experimental PL characterization showed a broad emission band centered...
Figure 5. Model results for an InAsN QD: (a) valence band (red line) and conduction band (blue line) profiles along growth direction—energies of two confined levels are indicated as blue (electron ground state), light blue (first excited electron level) dashed lines; purple continuous lines (heavy hole ground state), and light red dashed lines (first heavy hole excited level); (b) spectrum of spontaneous power density for confined electron-heavy hole transition as function of energy with indications of emission from QD ground states (QD$_0$), QD excited states (QD$_1$) and InGaAs CLs; (c) calculated probability density for confined electrons for ground state; (d) calculated probability density for confined heavy holes for ground state.

at 0.820 eV [12]. This slight disagreement can be attributed to higher uncertainties in the values of sizes and compositions of the considered nanostructures.

In figures 4(a) and (b) the band profiles and calculated energy levels along the vertical and horizontal axes are presented: due to strain effects and staggered band alignment, the minimum of the valence band occurs outside the QDs and this causes holes to be localized in the GaSb capping layer on the sides of the QD, as shown in figure 4(e). This spatial separation results in a highly reduced spontaneous power density for the QD$_0$ emission (see spectrum of figure 4(c)), as compared to type-I structures described above, of about three orders of magnitude.

On the other hand, there is a relevant separation between the electron ground and excited levels of 52 meV, that allows well-separated QD emission lines, as shown in figure 4(c).

In this system the calculated InAs WL energy level results to be 1.103 eV, thus the GaSb layer, that has a bandgap of 1.090 eV, can be considered as the dominant escaping channel for thermally activated carriers; hence, the energy barrier for thermal emission quenching of confined carriers results to be 300 meV.

These calculated values compare with experimental PL values of 1.050 eV for the GaSb layer and around 1.150 eV for the InAs WL [12]: the overestimation of such energies might come from uncertainties in the actual values of the composition of the GaSb layer, as discussed above for the case of the QD emission energies.
Table 1. Relevant quantities for QD systems considered.

| Material system/substrate | Type | QD emit-power density (W/eV) | Energy difference $E_{e0}$–$E_{e1}$ (meV) | Energy difference $E_{h0}$–$E_{h1}$ (meV) | QD-WL/CL energy separation (meV) | FSS (µeV) | $g^2(0)$ | Zero phonon line FWHM (meV) |
|--------------------------|------|-----------------------------|------------------------------------------|------------------------------------------|---------------------------------|--------|--------|--------------------------|
| Metamorphic InAs/InGaAs on GaAs | I/II | 1.86 $10^{-9}$ | 12 | 4 | 19.3 | 5.4 ± 3.0 [35] | $<10$ [8] | 0.003 ± 0.137 [8] | 0.3 ± 0.12 [8] | 0.059 [8] |
| InAs/InP on InP | I | 1.53 $10^{-9}$ | 57 | 26 | 312 | 0–4 ± 1.0 [9] | 0.13 ± 0.09 [11] | 0.33 ± 0.13 [16] | 0.05 [11] |
| In(Al)GaAs/InAlGaAs on InP | I | 9.0 $10^{-9}$ | 17 | 4 | 214 | 20 [11] | 0.33 ± 0.13 [16] | 0.05 [11] |
| InAs/GaAsSb on Si | II | 7.65 $10^{-13}$ | 52 | 0.7 | 300 | n.a. | n.a. | 1.3–5 [12] |
| InNAs on GaAs | I | 0.3 $10^{-9}$ | 36 | 9 | 600 | n.a. | n.a. | n.a. |

4.4. InAsN-GaAs QDs

The incorporation of N into InAs QDs was proposed almost 20 years ago as a method to consistently redshift its emission towards 1.55 µm due to the very large bandgap bowing of diluted III–As–N alloys [49, 50]. Despite this, the very first encouraging results were later hampered by the discovery that even a very low amount of nitrogen results in strong reduction of QD emission efficiency due to an increase of defects in the nanostructure. Most probably due to this issue, any report on the measurement of single photons in the C-band from In(Ga)AsN QDs is yet to be published. Nevertheless, research work is still devoted to this challenging material, hence we have included it in these theoretical calculations, hoping that soon some breakthrough will allow the defect-related problem to be solved.

For this case, we relied on the results of papers reporting the achievement of 1.55 µm emission from In(Ga)NAs QDs [51, 52] with a composition value of nitrogen of about 4%, considered as an average value taken from available experimental data.

In these works, precise values of sizes and composition of QDs were not reported: therefore, for the sake of argument, we considered InAsN QDs of truncated conical shape with standard sizes of 20 nm for diameters and 6 nm for heights. The WL state was calculated under the hypothesis of having a 1.6 ml layer of the same InAsN material of QDs. Material parameters for the low-N InNAs material were calculated on the basis of the most reliable values for the large bowing parameters [23].

The calculated QD energy levels indicate an expected emission energy of 0.786 eV, while to date the PL emission energy recorded for 4% of N is observed at 0.810 [51], although it should be noted that values of actual nitrogen incorporation could be prone to large uncertainties.

The results of the calculations, shown in figure 5, indicate that the holes in the ground states are localized on the side of the QD, leading to a reduction of the spatial overlap with the electron wavefunctions. This increased separation between confined particles results in the physical effect of a decrease of the recombination probability that causes a reduction of the intrinsic spontaneous power density in comparison with InAs/InP QDs or metamorphic QDs of almost an order of magnitude, as shown in the optical spectrum of figure 5(b). Thanks to the large band discontinuities with the GaAs CLs, many confined states were found, thus many QD emission lines are present in the spectrum. Moreover, a calculation of the expected WL emission has given a value of 1.396 eV, bringing the energy separation between QDs and WL to a very high value of 600 meV, the largest for all systems considered here. This value is very similar to the emission energy of InAsN/GaAs quantum wells, reported to be at 1.370 eV for an N composition of 4.4% [53].

5. Conclusions

To provide the reader with a quick view and to summarize the results, we present in table 1 the calculated relevant quantities for single-photon emission, as discussed in the Introduction:

- spontaneous power density for QD emission at 10 K in W/eV
- difference in energy between ground and excited state levels for electrons ($E_{e0}$–$E_{e1}$) and holes ($E_{h0}$–$E_{h1}$) in meV
- energy distance between QD levels and channels for thermal escape of carriers in meV
We have included in the table values reported in the literature of the FSS in $\mu$eV, of the $g^{(2)}(0)$ second-order autocorrelation function and of the zero-phonon line (ZPL) width at low temperature, when available from the literature.

For entangled photon emission, the FSS value should be lower than the ZPL emission linewidth. To the best of the authors’ knowledge, up to today no reports on measurements or calculation of FSS for InAs/GaAsSb QDs and InAsN/GaAs QDs have been published.

By looking at table 1, some general conclusions on the strength and weaknesses of the different systems can be drawn: the two systems with the largest oscillation strength and, thus, the highest emission efficiency are InAs/InP and metamorphic InAs/InGaAs, while the Sb-based system, having type-II confinement, has the lowest.

The metamorphic system and the InAs/InAlGaAs (grown on InP) have the most closely spaced confined levels, with possible useful consequences for quasi-resonant pumping but potential limitations for higher-temperature operation. This is of particular relevance for the metamorphic InAs/InGaAs system where the confinement potential is very low, up to the point of risking having a type-II confinement configuration. Conversely, the largest energy barrier that carriers have to overcome to be captured by bulk or WL states is that of InAsN QDs.

Until now, FSS has been measured only for InP-based QDs and for metamorphic InAs/InGaAs ones with results hinting at possible entangled photon emission, particularly if techniques to reduce the FSS below the emission linewidth are used, such as strain engineering via piezoelectric actuators [55, 56].

From a technological point of view, it is evident that, at this stage, InP-based QDs allow us to obtain the most relevant results and that the research is more advanced in this material system. On the other hand, systems based on GaAs or Si are more interesting from an industrial point of view as these are the most preferred semiconductor platforms for electronic and photonic devices. For GaAs QD systems, however, it should be kept in mind that some design/growth issues still need to be addressed: (i) the degree of confinement for metamorphic QDs needs to be increased, in particular for higher-temperature quantum light emission, (ii) it would be advisable to increase the emission efficiency of type-II GaSb QDs, and (iii) more research effort is needed to obtain good material quality of InAsN QDs.

In any case, considering this review of available QD materials, it can be argued that epitaxial semiconductor QDs represent the best option to obtain an efficient and reliable source of quantum light in the telecom C-band, a fundamental element for the future development of quantum-based light communication systems.

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ORCID iD

L Seravalli https://orcid.org/0000-0003-2784-1785

References

[1] Salter C L, Stevenson R M, Farrer I, Nicoll C A, Ritchie D A and Shields A J 2010 An entangled-light-emitting diode Nature 465 594–7
[2] Gazzano O, Michaelis de Vasconcellos S, Arnold C, Nowak A, Galopin E, Sagnes I, Lanco L, Lemaitre A and Senellart P 2013 Bright solid-state sources of indistinguishable single photons Nat. Nanotechnol. 4 1425
[3] Aharonovich I, Englund D and Toth M 2016 Solid-state single-photon emitters Nat. Photon. 10 631–41
[4] Lo H, Curty M and Tamaki K 2015 Secure quantum key distribution Nat. Photon. 8 595–604
[5] Yuan Z, Kardynal B E, Stevenson R M, Shields A J, Lobo C J, Cooper K, Beattie N S, Pepper M and Pepper M 2002 Electrically driven single-photon source Science 295 102–5
[6] Claudon J, Bleuse J, Malik N S, Bazin M, Jaffrennou P, Gregersen N, Sauvan C, Lalanne P and Gerard J-M 2010 A highly efficient single-photon source based on a quantum dot in a photonic nanowire Nat. Photon. 4 174–7
[7] Arakawa Y and Holmes M J 2020 Progress in quantum-dot single photon sources for quantum information technologies: A broad spectrum overview Appl. Phys. Rev. 7 021309
[8] Paul M, Olbrich E, Höschle J, Schreier S, Kettler J, Portalupi S L, Jetter M and Michler P 2017 Single-photon emission at 1.55 $\mu m$ from MOVPE-grown InAs quantum dots on InGaAs/GaAs metamorphic buffers Appl. Phys. Lett. 111 33102
[9] Kors A, Reithmaier J P and Benyoucef M 2018 Telecom wavelength single quantum dots with very small excitonic fine-structure splitting Appl. Phys. Lett. 112 172102
[10] Dusanowski Ł, Syperek M, Misiewicz J, Somers A, Höfling S, Kamp M, Reithmaier J P and Splett G 2016 Single-photon emission of InAs/InP quantum dashes at 1.55 $\mu m$ and temperatures up to 80 K Appl. Phys. Lett. 108 163108
[11] Benyoucef M, Yacob M, Reithmaier J P, Kettler J and Michler P 2013 Telecom-wavelength (1.5 $\mu m$) single-photon emission from InP-based quantum dots Appl. Phys. Lett. 103 162101
12

[12] Orchard J R, Woodhead C, Wu J, Tang M, Beanland R, Noori Y, Liu H, Young R J and Mowbray D J 2017 Silicon-based single quantum dot emission in the telecom C-band ACS Photon. 4 1740–6

[13] Auf der Maur M, Penazzi G, Romano G, Sacconi F, Pecchia A and Di Carlo A 2011 The multiscale paradigm in electronic device simulation IEEE Trans. Electron Devices 58 1425–32

[14] Le Ru E C, Fack J and Murray R 2003 Temperature and excitation density dependence of the photoluminescence from annealed InAs/GaAs quantum dots Phys. Rev. B 67 245318

[15] Seravalli L, Trevisi G, Frigeri P, Franchi S, Geddo M and Guizzetti P 2009 The role of wetting layer states on the emission efficiency of InAs/GaAs metamorphic quantum dot nanostructures Nanotechnology 20 237503

[16] Carmesin C et al 2018 Structural and optical properties of InAs/(In)GaAs/GaAs quantum dots with single-photon emission in the telecom C-band up to 77 K Phys. Rev. B 98 125407

[17] Barette D, De Angelis R, Prosposito P, Auf der Maur M, Casalboni M and Pecchia A 2014 Model of a realistic InP surface quantum dot extrapolated from atomic force microscopy results Nanotechnology 25 195201

[18] Seravalli L, Trevisi G and Frigeri P 2013 Calculation of metamorphic two-dimensional quantum energy system: application to wetting layer states in InAs/GaAs metamorphic quantum dot nanostructures J. Phys. D: Appl. Phys. 46 184309

[19] Sacconi F, Auf der Maur M and Di Carlo A 2012 Optoelectronic properties of nanocolumns InN/GaN/GaN LEDs IEEE Trans. Electron Devices 59 2970–87

[20] Poreo1otko M and Di Carlo A 2006 Elasticity theory of pseudomorphic heterostructures grown on substrates of arbitrary thickness J. Phys. D: Appl. Phys. 39 104

[21] Chuang S and Chang C 1996 K-p method for strained wurzite semiconductors Phys. Rev. B 54 2491–504

[22] Seravalli L, Trevisi G and Frigeri P 2018 Modelling of metamorphic quantum dots for single photon generation at long wavelength Semicond. Sci. Technol. 33 95018

[23] Vurgafman I, Meyer J R and Ram-Mohan I R 2001 Band parameters for III-V compound semiconductors and their alloys J. Phys. D: Appl. Phys. 34 5815–75

[24] Takenoto K, Takatsui M, Hirose S, Yokoyama N, Sakuma Y, Usuki T, Miyazawa T and Arakawa Y 2007 An optical horn structure for single-photon source using quantum dots at telecommunication wavelength J. Phys. D: Appl. Phys. 40 81720

[25] He L, Gong M, Li C F, Guo G C and Zunger A 2008 Highly reduced fine-structure splitting in InAs/InP quantum dot offerting an efficient on-demand entangled 1.55-µm photon emitter Phys. Rev. Lett. 101 157405

[26] Dion C, Desjardins P, Shintov N, Robertson M, Schiettekatte F, Poole P and Raymond S 2008 Intermixing during growth of InAs self-assembled quantum dots in InP: A photoluminescence and tight-binding investigation Phys. Rev. B 77 75338

[27] Carmesin C et al 2017 Interplay of morphology, composition, and optical properties of InAs/GaAs quantum dots emitting at the 1.55-µm telecom wavelength Phys. Rev. B 96 235309

[28] Sanguinetti S, Guazzi M, Grilli E, Gurioli M, Seravalli L, Frigeri P, Franchi S, Capizzi M, Mazza1ucato S and Polimeni A 2008 Effective phonon bottleneck in the carrier thermalization of InAs/GaAs quantum dots Phys. Rev. B 78 085313

[29] Yacob M, Reithmaier J P and Benyoucef M 2014 Low-density InP-based quantum dots emitting around the 1.5 µm telecom wavelength range Appl. Phys. Lett. 104 022113

[30] Xin Y C, Vaughan L G, Dawson L R, Stintz A, Lin Y Y, Lester L F and Huffaker D L 2003 InAs quantum-dot GaAs-based lasers grown on AlGaAsSb metamorphic buffers J. Phys. D: Appl. Phys. 36 2133–5

[31] Semenova E S et al 2004 Metamorphic growth for application in long-wavelength (1.3–1.55 µm) lasers and MODFET-type structures on GaAs substrates Nanotechnology 15 S283–7

[32] Seravalli L, Frigeri P, Trevisi G and Franchi S 2008 1.59 µm room temperature emission from metamorphic InAs/GaAs quantum dots grown on GaAs substrates Appl. Phys. Lett. 92 211304

[33] Seravalli L, Frigeri P, Nasi L, Trevisi G and Bocchi C 2010 Metamorphic quantum dots: quite different nanostructures J. Phys. D: Appl. Phys. 43 044324

[34] Ghanad-Tavakoli S, Naser M A, Thompson D A and Jamal Deen M 2009 Experimental characterization and theoretical modeling of the strain effect on the evolution and interband transitions of InAs quantum dots on Inx Ga1-x As (0.0 ≤ x ≤ 0.3) metamorphic pseudosubstrates on GaAs wafers J. Phys. D: Appl. Phys. 42 235335

[35] Olbrich F, Höschle J, Müller M, Kettler J, Luca Portalupi S, Paul M, Jetter M and Michler P 2017 Polarization-entangled photons from an InGaAs-based quantum dot emitting in the telecom C-band Appl. Phys. Lett. 111 133106

[36] Portalupi S L, Jetter M and Michler P 2019 InAs quantum dots grown on metamorphic buffers as non-classical light sources at telecom C-band: a review Semicond. Sci. Technol. 34 053001

[37] Skolnick M S and Mowbray D J 2004 Self-assembled semiconductor quantum dots: fundamental physics and device applications Annu. Rev. Mater. Res. 34 181–218

[38] Golovynskyi S, Datsenko O, Seravalli L, Kozak O, Trevisi G, Frigeri P, Babichuk I S, Golovynska I and Qu J 2017 Deep levels in InAs/GaAs quantum dot structures with different composition of the embedding layers Semicond. Sci. Technol. 32 125001

[39] Golovynskyi S, Datsenko O I, Seravalli L, Trevisi G, Frigeri P, Babichuk I S, Golovynska I, Li B and Qu J 2019 Defect influence on in-plane photocurrent of InAs/GaAs quantum dot array: long-term electron trapping and Coulomb screening Nanotechnology 30 305701

[40] Seravalli L, Trevisi G and Frigeri P 2012 2D–3D growth transition in metamorphic InAs/GaAs quantum dots Cryst. Eng. Comm. 14 1155–60

[41] Seravalli L, Gioannini M, Cappelluti F, Sacconi F, Trevisi G and Frigeri P 2016 Broadband light sources based on InAs/GaAs metamorphic quantum dots J. Phys. D: Appl. Phys. 49 143102

[42] Seravalli L, Trevisi G, Frigeri P, Royce R J and Mowbray D J 2012 Energy states and carrier transport processes in metamorphic InAs quantum dots J. Phys. D: Appl. Phys. 45 085309

[43] Seravalli L, Trevisi G and Frigeri P 2012 Design and growth of metamorphic InAs/GaAs quantum dots for single photon emission in the telecom window Cryst. Eng. Comm. 14 6833–42

[44] Lee B, Baek J H, Lee J H, Choi S W, Jung S D, Han W S and Lee E H 1996 Optical properties of InGaAs linear graded buffer layers on GaAs grown by metalorganic chemical vapor deposition Appl. Phys. Lett. 68 2973–5

[45] Seravalli L, Trevisi G, Frigeri P, Rossi F, Buffagni E and Ferrari C 2013 Wetting layer states in low density InAs/GaAs quantum dots from sub-critical InAs coverages J. Phys. D: Appl. Phys. 46 315101

[46] Ripalda J M, Granados D, Gonzalez Y, Sánchez A M, Molina S I and Garca J M 2005 Room temperature emission at 1.6 µm from InAs/GaAs quantum dots capped with GaAsSb Appl. Phys. Lett. 87 202108
[47] Liu H, Steer M J, Badcock T J, Mowbray D J, Skolnick M S, Suarez F, Ng J S, Hopkinson M and David J P R 2006 Room-temperature 1.6 µm light emission from InAs/GaAs quantum dots with a thin GaAsSb cap layer J. Phys. D: Appl. Phys. 99 46104

[48] Ulloa J M, Llorens J M, Del Moral M, Bozkurt M, Koenraad P M and Hierro A 2012 Analysis of the modified optical properties and band structure of GaAs 1 – x Sb x - capped InAs/GaAs quantum dots J. Phys. D: Appl. Phys. 112 074311

[49] Sopanen M, Xin H P and Tu C W 2000 Self-assembled GaInNAs quantum dots for 1.3 and 1.55 µm emission on GaAs Appl. Phys. Lett. 76 994–6

[50] Bais G, Cristofoli A, Jabeen F, Piccin M, Carlino E, Rubini S, Martelli F and Franciosi A 2005 InAsN/GaAs(N) quantum-dot and InGaNAs/GaAs quantum-well emitters: A comparison Appl. Phys. Lett. 86 233107

[51] Milla M J, Guzmán A, Gargallo-Caballero R, Ulloa J M and Hierro A 2011 Optimization of InGaAsN(Sb)/GaAs quantum dots for optical emission at 1.55 µm with low optical degradation J. Cryst. Growth 323 215–8

[52] Gargallo-Caballero R, Guzmán A, Hopkinson M, Ulloa J M, Hierro A and Calleja E 2009 Dependence of N incorporation into (Ga)InAsN QDs on Ga content probed by rapid thermal annealing Phys. Status Solidi c 6 1441–4

[53] Kuboya S, Thieu Q T, Ono W, Nakajima F, Katayama R and Onabe K 2007 MOVPE and characterization of InAsN/GaAs multiple quantum wells J. Cryst. Growth 298 544–7

[54] Muñoz-Matutano G, Barrera D, Fernández-Pousa C R, Chulia-Jordan R, Seravalli L, Trevisi G, Frigeri P, Sales S and Martínez-Pastor J 2016 All-optical fiber hanbury brown & twiss interferometer to study 1300 nm single photon emission of a metamorphic InAs quantum dot Sci. Rep. 6 22214

[55] Trotta R, Martín-Sánchez J, Daruka I, Ortix C and Rastelli A 2015 Energy-tunable sources of entangled photons: a viable concept for solid-state-based quantum relays Phys. Rev. Lett. 114 150502

[56] Trotta R, Martín-Sánchez J, Wildmann J S, Piredda G, Reindl M, Schimpf C, Zallo E, Stroj S, Edlinger J and Rastelli A 2016 Wavelength-tunable sources of entangled photons interfaced with atomic vapours Nat. Commun. 7 10375