

Quantum dots on GaAs substrates as integration-ready high-performance single-photon sources at telecommunication wavelengths

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The development of deterministic single-photon sources emitting in the telecommunication bands is a key challenge for quantum communication and photonic quantum computing. Here, we investigate the optical properties and single-photon emission of molecular beam epitaxy (MBE) grown semiconductor quantum dots (QDs) emitting in the telecom O- and C-bands. The QDs are embedded in an InGaAs matrix with fixed indium content grown on top of a compositionally graded InGaAs buffer. This structure allows for the future implementation of electrically contacted nanocavities to enable high-quality and bright QD emission. In detailed optical characterizations we observe linewidths as low as 50 μeV , close to the spectrometer resolution limit, low fine structure splittings close to 10 μeV , and $g^{(2)}(0)$ values as low as 0.08. These results advance the current performance metrics for MBE-grown QDs on GaAs substrates emitting in the telecom bands and showcase the potential of the heterostructures presented for further integration into photonic devices.

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Advances in quantum communication require high-performance single-photon sources, capable of generating pure, indistinguishable photons with high efficiency. Semiconductor quantum dots (QDs) emitting at 950 or 785 nm have emerged as promising candidates for single-photon sources, due to their excellent optical properties and potential for integration into scalable photonic devices [1–7]. Significant progress has recently been reported in the optimization of this system, such as spectral tuning mechanisms, cavity integration, and strain engineering [8–10].

In fiber-based quantum networks, the communication range is limited by optical attenuation, which scales exponentially with distance. This constraint makes the realization of sources emitting in the telecommunication bands crucial, as they minimize photon losses in optical fibers and enable practical long-distance quantum communication [11]. Among the most promising candidates for telecom applications are InAs QDs grown on InP substrates,

as they naturally emit in the C-band [12–14]. Specifically, the performance of QDs as a single-photon source can be improved by embedding them in photonic resonators to enhance photon extraction and coherence properties [15–17]. While InP-based QDs exhibit favorable emission wavelengths due to their lower lattice mismatch, further enhancing the extraction efficiency using distributed Bragg reflectors (DBRs) is challenging due to the relatively low refractive index contrast of the materials used for InP-based DBRs compared with GaAs-based ones.

On the other hand, GaAs substrates are less brittle than InP ones and allow for the growth of lattice-matched binary DBR systems with high refractive index contrast. Importantly, for GaAs substrates, an effective method for shifting QD emission to the telecom bands is to grow compositionally graded InGaAs layers directly beneath the InAs QD layer [18–21]. However, plastic relaxation of the lattice constant along the graded layer leads to the formation of dislocations, thereby complicating the implementation of electrically contacted devices. Additionally, the QD layer is grown on top of a residually strained region within the graded structure, further complicating device integration [20,22]. Despite these challenges, a nonlinear grading profile was proposed to reduce the thickness of the graded layer and thus fabricate a circular Bragg grating to enhance the extraction efficiency. Nonetheless, the relaxed portion of the layer was included in the final resonator,

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thus limiting the implementation of additional electrical contacts [23].

A potential solution that addresses the limits associated with the direct growth of QDs on a graded layer is to embed the QDs within a relaxed InGaAs matrix grown on top of the compositionally graded layer, resulting in reduction of both dislocation density and residual strain close to the QD layer [24–26]. Recently, such an approach has been optimized to obtain bright QD emission in the telecom O- and C-bands [26]. However, comprehensive studies of the optical properties of this heterostructure such as optical linewidths, fine structure splittings (FSSs), lifetimes, and the single-photon nature of the emission are still missing.

In this paper, we investigate the optical properties of InAs QDs embedded in mostly relaxed InGaAs matrices grown on top of graded InGaAs buffers placed on nearly lattice-matched DBRs with emission across the telecom O- and C-bands. Specifically, microphotoluminescence (μ -PL) and time-resolved characterizations allow us to analyze key metrics such as linewidth, FSS, and excitonic lifetime, and to demonstrate the single-photon nature of the emission via photon statistics measurements.

The samples studied were grown with a solid source Veeco Gen II molecular beam epitaxy (MBE) system on undoped (001) GaAs substrates. Two different samples were grown, where the layer thicknesses and In composition were optimized for emission of the QDs in the O- and C-band. Throughout this paper, these two samples are labeled sample **O** and **C**, respectively. Figure 1(a) shows the layer structure of the samples studied. First, a 200-nm-thick GaAs buffer layer was grown on the (001) GaAs substrate to achieve an optimal epitaxial surface. Subsequently, 10 alternating GaAs/AlAs DBR pairs were incorporated into each sample with their thicknesses designed to enhance the extraction efficiency of the QD emission in the center of the respective telecom band.

To ensure that the total optical thickness between the DBRs and the semiconductor-air interface forms a 3λ cavity, an additional GaAs buffer layer is deposited on top of the DBRs, with thicknesses of 40 nm and 30 nm for samples **O** and **C**, respectively.

Figure 1(b) shows the In content profiles across both samples, excluding the DBR layers. The reported In profiles were calculated from the In-flux equivalent growth rate as a function of the In cell temperature at fixed Ga flux [26]. During the deposition of the graded $\text{In}_y\text{Ga}_{1-y}\text{As}$ layers, the Ga growth rate was kept at $1 \text{ \AA/s}$, while the In growth rate was increased from $0.05 \text{ \AA/s}$ to $0.53 \text{ \AA/s}$ for sample **O** and up to $0.75 \text{ \AA/s}$ for sample **C**. This resulted in maximum In contents of 35% and 43%, respectively. Using an In grading rate similar to the one reported in Ref. [26], the thicknesses of the compositionally graded layers were determined to be 730 nm and 880 nm for sample **O** and **C**, respectively.

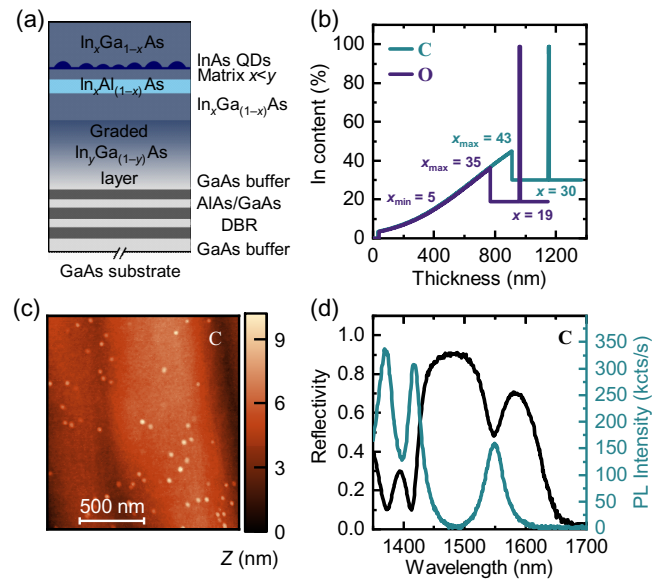


FIG. 1. (a) Schematic of the sample structure. The InAs quantum dots (QDs) are embedded in an InGaAs matrix with fixed indium content grown on top of a compositionally graded InGaAs layer. An AlAs/GaAs distributed Bragg reflector (DBR) is grown on a (001) GaAs substrate. (b) Profile of the In content across heterostructures **O** (purple) and **C** (green) excluding the DBR layers. (c) Atomic force microscope scan of a sample similar to heterostructure **C** showing uncapped QDs grown on top of an InGaAs matrix. (d) Reflectivity measurements (black) and ensemble photoluminescence (PL) spectrum of the QD emission (green) measured via nonresonant excitation at 10 K from sample **C**. Both spectra are recorded at the same position on the wafer.

An equivalent thickness of 2.2 monolayers of InAs forming the QDs was embedded within an InGaAs matrix with In compositions of 19% (30%) for sample **O** (sample **C**). The substrate rotation was stopped during the growth of the QD layer to achieve a QD density gradient. The QD layers were positioned in an antinode of the standing electric field, 190 nm (sample **O**) and 220 nm (sample **C**) from the surface. In order to prevent further propagation of dislocations into the matrix, a 20-nm-thick InAlAs layer, with In composition matching that of the InGaAs matrix, was introduced in both samples. Further details regarding the growth process can be found in Refs. [20,26].

We investigated the surface morphology using a Bruker Multimode 8 atomic force microscope (AFM) in tapping mode. Figure 1(c) shows an AFM topography scan of an uncapped reference sample consisting of InAs QDs on an InGaAs matrix grown on top of the graded buffer, taken from a high-density (approximately $2.2 \times 10^9 \text{ cm}^{-2}$) region. The surface undulations with a width of $1 \mu\text{m}$ and a height of 10 nm are typical for metamorphic structures [18,20,27] where QD nucleation is more favorable on convex parts of the surface [20,23].

After the growth, reflectivity measurements and ensemble PL measurements are used to confirm the correct design of the cavity. The measurements were performed by using a helium flow cryostat operating at 10 K. We analyzed the detected PL and reflectivity signal using a spectrometer equipped with a thermoelectrically cooled InGaAs linear array detector. The ensemble PL spectroscopy was performed under continuous-wave (CW) nonresonant excitation at 660 nm. Reflectivity measurements were carried out by excitation with a tungsten halogen light source. As an example, Fig. 1(d) shows the normalized reflectivity (black) and PL (green) spectra from sample **C** recorded at a temperature of 10 K at the same position on the wafer. The reflectivity corresponds to the typical reflectivity of a DBR stop band, with a cavity dip in the center. The layer structure selectively suppresses light outcoupling within specific wavelength ranges while enhancing it near the cavity dip. Notably, the PL spectrum of the QDs, presented alongside the reflectivity data, reveals a pronounced enhancement of QD emission near the cavity dip at 1550 nm. This is due to the positioning of the QD layer near an antinode of the standing wave field.

In the following, we present a detailed characterization of the optical properties of single QDs under above-band excitation, including power-dependent, polarization-resolved, and time-resolved PL measurements. From these measurements, the linewidth, FSS, and radiative lifetime of exciton transitions are deduced. The optical characterization of single QDs was carried out using a conventional confocal microscopy μ -PL setup. The samples were placed in an AttoDRY800 closed-cycle cryostat operating at 4 K. The excitation was provided by a nonresonant CW Toptica continuously tunable laser at 898 nm. The PL signal was analyzed using an Andor Shamrock 750 spectrometer and detected by an InGaAs CDD iDus 419, at a temperature of -66°C .

Figures 2(a) and 2(b) present representative μ -PL spectra from sample **C** and sample **O**, respectively. Sharp emission lines resulting from different excitonic transitions are visible. Those peaks are attributed to neutral exciton (X), trion, and biexciton (XX) transitions. This assignment is made based on power- and polarization-dependent measurements. Importantly, as the DBR enhances the extraction efficiency it enables clean spectra with high signal-to-noise ratio, which allows for fitting the data with small errors.

Figure 2(f) shows the linewidths (full width at half maximum, FWHM) of X transitions from the emission spectra of 18 individually characterized QDs for each telecom band. The extracted FWHM values are in the range 50.0–243.0 μeV with a median value of $124.0 \pm 6.4 \mu\text{eV}$ for sample **O** and $119.0 \pm 6.8 \mu\text{eV}$ for sample **C**. With the exception of some outliers, most data points are within the 60.0–150.0 μeV range. The measured minima are $50.0 \pm 0.9 \mu\text{eV}$ for sample **O** and $62.0 \pm 4.0 \mu\text{eV}$ for sample **C**.

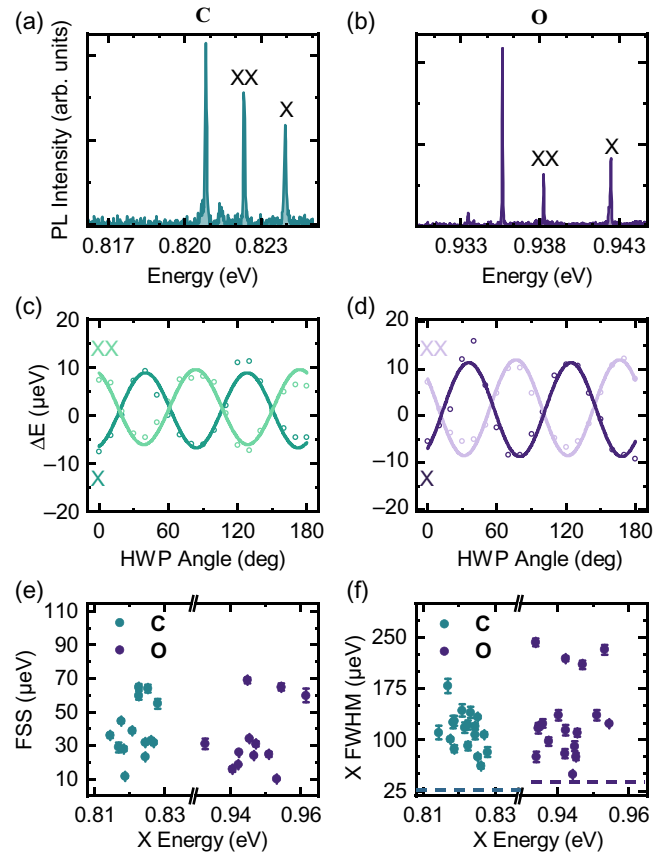


FIG. 2. (a),(b) Microphotoluminescence (μ -PL) spectra of sample **C** and sample **O**, recorded via above-bandgap excitation. (c),(d) Polarization-resolved μ -PL measurements of samples **C** and **O**, respectively, as a function of the rotation angle of the half wave plate (HWP) under nonresonant excitation. The fine structure splitting (FSS) values for the QD emission of (d) and (c) are $19.0 \mu\text{eV} \pm 0.4 \mu\text{eV}$ and $14.0 \mu\text{eV} \pm 0.5 \mu\text{eV}$, respectively. (e) FSS values of X emissions as a function of the emission energy. (f) Linewidths (full width at half maximum, FWHM) of measured neutral exciton (X) transitions on both samples as a function of the emission energy. The purple and green dashed lines indicate the resolution limits of the spectrometer at both wavelengths.

This is close to the resolution limit of the spectrometer. For sample **O** (1310 nm) the resolution limit is $35.0 \mu\text{eV}$, while for sample **C** (at 1550 nm) it is $23.0 \mu\text{eV}$. The resolution limits are illustrated as green and purple dashed lines, respectively.

Previous studies of MBE-grown Stranski-Krastanov (SK) QDs grown on top of compositionally graded layers on (001) GaAs substrates report median values of FWHM of X emission of $300.0 \mu\text{eV}$ in the C-band [21] and of $250.0 \mu\text{eV}$ for a charged exciton [19]. For MBE-grown, droplet epitaxy (DE) QDs on (111) $\bar{A}$ GaAs substrates values in the range of 100.0–550.0 μeV are reported [28].

Meanwhile, for QDs grown using metalorganic vapor phase epitaxy (MOVPE) on InP substrates, Ref. [29]

reports values of $119.0 \mu\text{eV}$, and Ref. [15] reports a mean value of $557.2 \mu\text{eV}$. Therefore, the FWHM values reported here are lower than those reported for other self-assembled, MBE-grown QDs on graded layers and on GaAs substrates of different orientations. We also observe an improvement over values measured on MOVPE-grown QDs on InP substrates.

All of the values mentioned above were obtained under nonresonant excitation. Employing resonant excitation techniques would significantly reduce spectral broadening resulting from charge noise, and therefore allow one to observe linewidths closer to the transform limit, that is, the linewidth resulting from the finite lifetime of the excited states [30]. For instance, in self-assembled MBE-grown QDs on GaAs substrates a reduction in average linewidth from $40 \pm 14 \mu\text{eV}$ (obtained under nonresonant excitation) to $14 \pm 2 \mu\text{eV}$ (under resonance fluorescence) has been achieved [31]. Quasiresonant excitation techniques also help mitigate spectral broadening resulting from charge noise. Examples of this include *p*-shell excitation on self-assembled, MBE-grown QDs on InP substrate yields linewidths up to $29 \mu\text{eV}$ [32], while longitudinal acoustic (LA)-phonon and SUPER excitation schemes on MOVPE-grown QDs on GaAs substrate both result in linewidths of approximately $20 \mu\text{eV}$ [33]. In addition to yielding decreased linewidth values [30–33], we expect a transition toward resonant excitation techniques to result in further benefits for the optical properties, such as improved purity [33,34] and reduced relaxation time [34].

As the FSS values play a crucial role in realizing polarization-entangled photon sources [35–37], we carried out a polarization-resolved analysis of the emission of 13 QDs under above-bandgap excitation for samples **O** and **C**. For each QD, spectra with a linear polarizer and half waveplate (HWP) in the detection channel were taken as a function of the angle of the half wave plates. The spectra were then fitted to extract the center position of the X and XX peaks. The results of two example measurements from samples **C** and **O** are presented in Figs. 2(c) and 2(d). The figures show the extracted deviation of the emission energy from its mean value as a function of the rotation angle of the HWP. In both cases, counteroscillating wavelengths for X and XX are observed. Sine fits (continuous lines) to the data reveal FSS values of $19.0 \pm 0.4 \mu\text{eV}$ (sample **O**, purple) and $12.0 \pm 0.5 \mu\text{eV}$ (sample **C**, green).

The extracted values of the FSS for all investigated QDs are presented in Fig. 2(e) as a function of their emission energies. For the majority of the measured QDs we extract FSS values up to $50.0 \mu\text{eV}$, with median values of $28.0 \pm 1.6 \mu\text{eV}$ for **O** and $34.0 \pm 1.4 \mu\text{eV}$ for **C**. Importantly, the smallest observed values are $10.0 \pm 0.4 \mu\text{eV}$ for **O** and $12 \pm 0.55 \mu\text{eV}$ for **C**.

To assess our results, we compare the extracted values to those published in literature. For QDs grown using the

SK approach, reported mean values are $176.0 \pm 9.0 \mu\text{eV}$ for MBE-grown QDs on InP [38] and in the region of $123.0 \mu\text{eV}$ for MOVPE-grown QDs on InP [39]. For SK-grown QDs on GaAs substrates, where the FSS is affected by the higher lattice mismatch and consequent dot asymmetry, reported values for MBE-grown QDs range between $16.0 \mu\text{eV}$ and $136.0 \mu\text{eV}$, which were reduced by applying external strain [35], and $50.0 \mu\text{eV}$ [21] for (001)-oriented substrates. Meanwhile, for QDs grown using DE, which results in lower FSS values due to the improved symmetry of the QDs, reported mean values are $42.0 \pm 7.0 \mu\text{eV}$ with a minimum of $12.0 \pm 2.0 \mu\text{eV}$ for MBE-grown QDs on InP substrates [38] and $50.0 \pm 5.0 \mu\text{eV}$ for an MOVPE-grown QD on an InP [13]. For MBE-grown QDs on (111)*A*-oriented substrates, values of $141.2 \pm 4.2 \mu\text{eV}$ are reported [28]. Notably, the reported FSS values are lower than those reported for QDs grown on InP substrates via SK growth and remarkably comparable to DE-grown QDs on InP, and they are comparable to other MBE-grown [21] and MOVPE-grown [18,23] QDs on graded layers on top of (001) GaAs substrates. We tentatively attribute this to the lower strain generated by this growth approach, which should result in more symmetric QDs.

To fully characterize the optical properties of the QD emission, we quantify the excited state lifetime τ via pulsed nonresonant excitation. To enable time-resolved measurements, we used pulsed excitation from a Coherent Chameleon Ti:sapphire laser, tuned to 785 nm with a repetition rate of 80 MHz . The laser pulses, originally in the femtosecond range, were stretched to the picosecond timescale using a custom-built $4f$ spectral filter. An NKT Photonics Origami pulsed laser, operating at the same wavelength with a repetition rate of 50 MHz , was additionally used to perform second-order autocorrelation measurements. The emitted transitions were spectrally filtered using a similar setup and detected by Single Quantum superconducting nanowire single-photon detectors. Time-tagging of detected photons was implemented using a qtools QuTag Standard time-correlated single-photon counting module.

Figures 3(a) and 3(b) present the time-resolved PL intensity of typical measurements of the X and XX transitions in samples **C** and **O**. They show exponential [Fig. 3(b)] and biexponential [Fig. 3(a)] decay behavior. The extracted τ values exhibit the expected [40] ratio of approximately 2 between XX and X lifetimes. For instance, the measurements presented in Fig. 3(b) (sample **O**) exhibit a monoexponential decay with $\tau^X = 1.70 \pm 0.01 \text{ ns}$ and $\tau^{XX} = 0.80 \pm 0.01 \text{ ns}$. For sample **C** [Fig. 3(a)], a biexponential decay function was required to accurately fit the experimental data for both transitions. This could be caused by the presence of additional processes related to, for example, defects and refilling of the QD by charge carrier trap states [21,31]. The extracted values are $\tau^X = 2.31 \pm 0.09 \text{ ns}$ and $\tau^{XX} = 1.63 \pm 0.03 \text{ ns}$. The subsequent

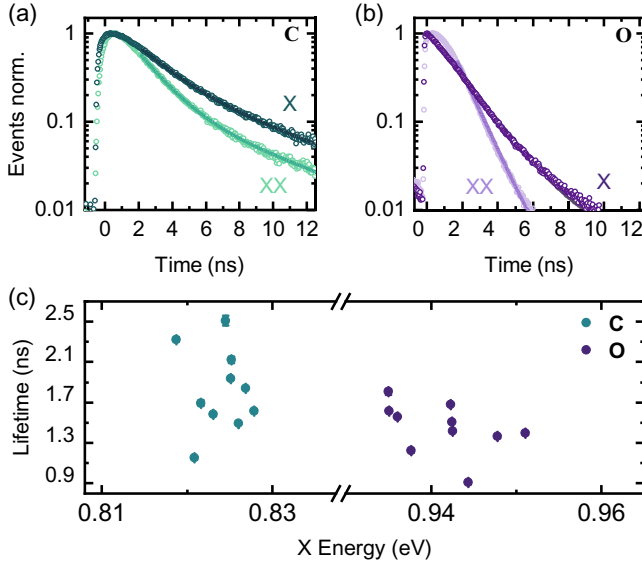


FIG. 3. (a),(b) Lifetime measurements of X and XX transitions on QDs from samples **C** and **O** recorded under nonresonant pulsed excitation. (c) Lifetime of measured X transitions as a function of the X emission energy.

slower decays amount to 19.29 ± 1.38 ns for X and to 8.00 ± 1.50 ns for XX.

Figure 3(c) shows the X lifetime of 10 QDs from each sample. The values lie within the range 0.94–2.50 ns with median values of 1.40 ± 0.01 ns for **O** and 1.80 ± 0.02 ns for **C**, respectively. The extracted X lifetime minima are 0.91 ± 0.02 ns for **O** and 1.15 ± 0.02 ns for **C**. Similar values are reported across the literature, without significant differences between SK-grown [18,21,23,31] and DE-grown [13,16] QDs nor between GaAs-based [18,23,31] and InP-based [13,16] structures. This indicates that the τ values we report do not significantly differ from those reported in other studies on non-cavity-integrated QD, across different growth approaches, methods, and substrate compositions.

Finally, we performed second-order autocorrelation measurements on trion states (selected due to their higher brightness over X states) to confirm the single-photon nature of the emission. For such measurements, we added a Hanbury Brown and Twiss setup after the spectral filter, employing a fiber-coupled beam splitter from OZ Optics. The results of typical measurements for both samples under CW excitation are presented in Figs. 4(a) and 4(b). In both cases the measured $g^{(2)}(0)$ values are significantly below 0.50, demonstrating the single-photon nature of the emitted light and a negligible background emission. By fitting we obtain $g^{(2)}(0)$ values of $g^{(2)}(0) = 0.08 \pm 0.01$ for sample **O** and $g^{(2)}(0) = 0.19 \pm 0.02$ for sample **C**. Note that the data in Fig. 4(a) exhibit a bunching behavior, indicative of blinking. This blinking behavior can be

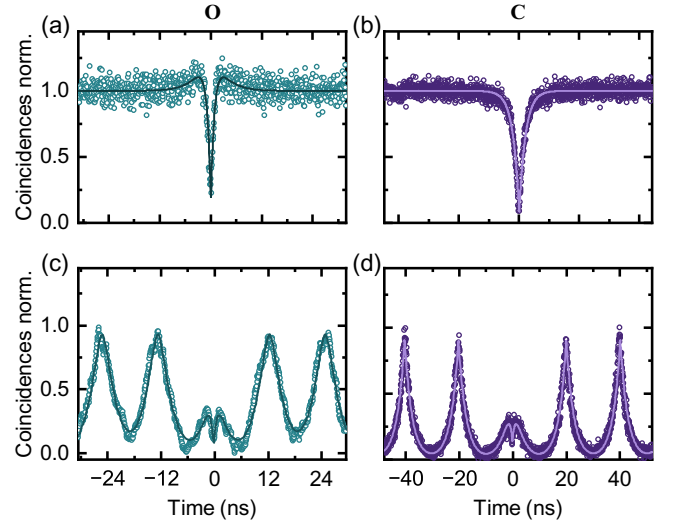


FIG. 4. (a),(b) Continuous-wave excitation $g^{(2)}(0)$ measurements on samples **C** and **O** at excitation powers of 30 nW and 5 μ W. (c),(d) Pulsed-excitation $g^{(2)}(0)$ measurements on **C** and **O**, carried out at a power of 200 nW and 35 μ W. The difference in timescale between the two figures is due to excitation with two different pulsed lasers, with repetition rates of 50 MHz and 80 MHz, respectively.

attributed, for example, to trapping of charge carriers, reexcitation, or the presence of dark states [31,39].

Typical second-order autocorrelation measurements under pulsed, above-band excitation are presented in Figs. 4(c) and 4(d) for samples **C** and **O**. Both measurements reveal an attenuated center peak with a sharp dip in its center. This behavior can be attributed to the nonresonant excitation scheme. A significant number of carriers are excited and trapped in the wetting layer or in other charge-trap states [13,41]. Upon a first recombination event, these carriers are subsequently captured by the QDs, resulting in the emission of secondary photons. Similar recapture dynamics have been observed in previous $g^{(2)}(0)$ measurements conducted under nonresonant excitation on QDs grown directly on compositionally graded InGaAs layers [18,21,42]. The presence of a visible dip in the center peak, combined with the results of the $g^{(2)}(0)$ measurements under CW excitation and the near-absence of background, hint at this phenomenon being responsible for the counts near time zero of the $g^{(2)}(0)$ value under pulsed excitation. In particular, this would be due to the chosen excitation scheme and to the higher excitation power required to conduct measurements under pulsed excitation. Recapture behavior as a function of quasiresonant or resonant excitation will, however, be investigated in detail in future studies, as it is beyond the scope of this paper. The different width and shape of the side peaks of Fig. 4(c) compared with Fig. 4(d) are caused by a rising onset in the population lifetime of the measured transition,

likely originating from the near-saturation excitation conditions and possible double excitation effects [31]. On the other hand, the discrepancy in the spacing between them originates from the use of another excitation laser with a different repetition rate.

These correlation measurements confirm the single-photon emission of the studied structure. Combined with the results from the linewidth and FSS measurement, they underline the potential of the sample structure studied.

In this paper, we have demonstrated the realization of high-quality single-photon emitters operating in the second and third telecom windows. Our design is based on InAs QDs embedded within a InGaAs matrix, grown on a compositionally graded InGaAs buffer to reduce dislocations. We found that the emission exhibits narrow linewidths even under nonresonant excitation and without implementing additional measures to control the charge environment, likely due to the improved dot symmetry and reduced dislocations in the QD matrix. As further evidence of this growth approach's benefits in terms of strain and dot shape, the FSS values we measured are comparable to those reported for QDs grown with approaches and materials known for yielding symmetric QDs characterized by small FSS values, such as DE on InP substrates. Moreover, we confirmed the single-photon nature of the emission, although the excitation scheme employed in these measurement results in charge carrier recapture, which negatively affects our extracted $g^{(2)}(0)$ values.

These results establish InGaAs-embedded QDs as strong candidates for single-photon sources in quantum communication systems operating within the telecom O- and C-bands. By minimizing the dislocation density in the matrix where the QDs are embedded, the growth approach presented will also open the way for the fabrication of electrically contacted InAs QDs embedded in GaAs-based resonators with telecom emission.

To further advance toward quantum communication applications, a transition to resonant excitation schemes would be beneficial, since it would allow for better quantification of the transition linewidth and eliminate the limitations caused by recapture dynamics observed by the autocorrelation measurements. Incorporating the heterostructure into piezoelectric actuators could further reduce the FSS, potentially enabling the use of the presented QDs as sources of entangled photon pairs. Moreover, embedding the presented QDs into nanocavities to enhance generation rates will enable brighter and purer emission, thus paving the way for more advanced quantum communication protocols.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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