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Effect of Submonolayer ZnS Shell on Biexciton Dynamics of Indium Phosphide Quantum Dots

Jie Meng, Qian Zhao, Weihua Lin, Tönu Pullerits,* and Kaibo Zheng*

Understanding high-order biexciton dynamics is important for the use of semiconductor quantum dots (QDs) in optoelectronic devices. The core-shell structure can be used to modulate biexciton dynamics by varying the shell thickness and core-shell energy band alignment. In this study, the biexciton dynamics in an unconventional case in which each QD is encapsulated by a submonolayer shell are demonstrated. The result of a transient absorption spectroscopic study shows that InP/ZnS core/shell QDs with submonolayer shell coverage exhibit a prolonged Auger lifetime. However, the QD size dependence of the Auger recombination time features two constant distinct stages instead of the typical monotonic volume scaling law in conventional QDs. It is attributed to the tradeoff between the enlarged QD size and quantum-well confinement for the Auger processes. However, the abrupt change between the two stages is due to the change in the shell coverage. This study provides a reference for the application of core-shell QDs in optoelectronic devices in which full coverage of the shell is not achieved.

1. Introduction

Over the recent decades, indium phosphide (InP) colloidal quantum dots (QDs) have garnered significant attention as a promising environmentally friendly optoelectronic material.^[1,2] The large exciton Bohr radius (10 nm) of InP allows the size of InP QDs to be adjusted to achieve the desired quantum confinement.^[3] However, similar to other III–V QDs, InP QDs are susceptible to surface oxidation and exhibit low electronic tolerance toward surface traps owing to the strong tetrahedral co-ordination of covalent bonds.^[4] This significantly restricts their

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application in optoelectronic and photovoltaic devices. However, these surface defects can be effectively reduced via hydrofluoric acid (HF) treatment with dangling surface P bonds coordinated by Fions.^[5] Alternatively, a core-shell structure can be established to passivate the surface defects.^[6,7] Recently, Jang et al. reported the exceptional performance of InP-based QD light-emitting diode (LED) using core-shell structures to passivate surface defects. The QD-LEDs achieved a theoretical maximum external quantum efficiency of 21.4%, a maximum brightness of 100 000 candelas per square meter, and an unprecedented lifetime of one million hours at 100 candelas per square meter.^[8] Additionally, the InP/ZnS coreshell QDs obtained in that study measured 507-728 nm. These QDs exhibited a small Stokes shift of 110-120 meV and

a narrow photoluminescence (PL) line width of 112 meV at 728 nm.^[9] Similarly, core–shell engineering is propelling advancements in solar energy and photocatalysis, thereby significantly improving the photovoltaic efficiency and photocatalytic activities.^[10] ZnS is the most typically used shell material owing to its similar lattice constant to InP, as well as its suitable band edge energy to form a type-I heterojunction with InP.^[11] In type-I core–shell QDs, large-bandgap shell materials can confine both electrons and holes, thus resulting in greater oscillator strength and a higher photoluminescence quantum yield (PLQY).^[2]

In addition to offering surface passivation, core–shell structures can affect Auger recombination in QDs.^[12] Auger recombination refers to a phenomenon in which the energy resulting from the recombination of an electron and hole is transferred to a third carrier or exciton, which significantly suppresses chargecarrier transport and collection in optoelectronic devices, particularly at high carrier densities.^[13] This phenomenon is ubiquitous in II–VI, III–V, and IV–VI semiconductors. The Auger lifetime of semiconductor QDs is affected significantly by their size.^[14] A universal linear scaling of biexciton lifetime (τ_{xx}) with the QD volume (V), known as V-scaling ($\tau_{xx} = \beta V$, β is the scaling coefficient with), has been observed in most semiconductor QDs.^[15] Such a scaling law is derived from the combined contribution from confinement-induced state mixing, carrier-carrier Coulomb coupling, and the surface states of QDs.^[16]

When the core-shell structures are formed, the scaling law in QDs can be perturbed owing to modifications in the band alignment and quantum confinement. Initially, the passivation ADVANCED SCIENCE NEWS www.advancedsciencenews.com

of surface trap states by the shell coating can significantly alter the Auger recombination time.^[17] However, from a broader perspective, in core–shell QDs, particularly those with a type-I structure, the excited charge carriers are confined within the quantum well, thus causing their wave functions to become spatially localized.^[18] Consequently, interaction among charge carriers is more likely to occur,^[19] and this increased interaction enhances the Auger recombination. Theoretical calculations confirmed that an increase in the potential barrier height of a quantum well can accelerate the Auger recombination rate.^[20] Nevertheless, these intense quantum confinements can be mitigated by increasing the shell thickness or by adopting a gradient core– shell structure.^[21]

However, in optoelectronic or photovoltaic applications, thick shells in core–shell QDs typically inhibit excited charge carrier extraction. In this case, an ultrathin shell or a submonolayer shell, whose surface trap states are selectively passivated without sacrificing the electron transfer efficiency, are preferred.^[22] Consequently, conventional confinement theory may not be applicable to the core–shell structure, thus affecting the Auger recombination dynamics of core–shell QDs.

Therefore, in this study, we investigate the dynamics of the Auger recombination and its volume-scaling law in benchmark InP/ZnS QDs with submonolayer shell coverage using transient absorption spectroscopy. Instead of observing the monotonic volume scaling law for the Auger rates typically observed in conventional QDs, we identify two distinct stages in the volume scaling plot. For small volume InP/ZnS QDs below 15 nm³, the τ_{xx} remains fixed at \approx 0.6 ps, whereas it increased abruptly by a factor of five to \approx 3 ps for QDs with volumes exceeding 15 nm³. We attribute this phenomenon to the tradeoff between the enlarged QD and the reduced coverage of the quantum well height in the relaxed quantum well confinement of larger QDs. The sharp transition of the Auger lifetime shown by QDs measuring 15 nm³ is caused by the abrupt change in the shell coverage. This study provides valuable insights into the effect of the shell structure on the Auger dynamics in QDs, thereby offering guidance for the optimization of the core-shell structure for QD-based optoelectronic devices.

2. Result and Discussion

2.1. QD Preparation and Characterization

To investigate the effect of the shell on the biexciton lifetime, we fabricated two sets of QDs: InP and InP/ZnS QDs, each comprising QDs with five different sizes. These QDs were synthesized based on previously reported methods using tris(diethylamino)phosphine as the phosphine precursor in the presence of Zn^{2+} additives. The particle sizes were regulated by the ratio of $ZnCl_2$ and ZnI_2 , as well as the temperature (details are provided in the Supporting Information).^[23] Figure 1 shows the Ultraviolet (UV)–visible absorption and PL spectra of the synthesized InP and InP/ZnS QDs with five distinct sizes. These QDs exhibited band-edge exciton absorption peaks at 480, 500, 540, 580, and 610 nm; herein, these samples are referred to as InP480, InP500, InP540, InP580, and InP610, respectively. The band-edge exciton absorption peak shift was due to size-dependent quantum confinement, which was confirmed via transmission electron microscopy (TEM) characterization (for details, see the Supporting Information). Based on the TEM images, the average particle size of the InP QDs increased from 2.8 to 4 nm. Similarly, the average particle size of the InP/ZnS QDs increased from 2.4 to 3.6 nm. For the pristine InP QDs (InP480, InP500, and InP540), the PL spectra were dominated by broad emission, which is attributed to sub-bandgap defect emission and band-edge exciton emission. Such defect emissions are more pronounced in smaller QDs with larger surface-to-volume ratios.^[6] When the ZnS shell was applied, the PL intensity of the QDs enhanced significantly, with a distinct and well-defined band-edge emission band. This was due to the effective surface passivation by the ZnS shell, as confirmed in previous studies.^[17]

However, compared with conventional core-shell QDs with full coverage of the shell, the QDs investigated in this study were coated with an ultrathin shell with submonolayer coverage. This was confirmed via elemental analysis using XPS. The average probe depth used in the XPS (3-5 nm) ensured the complete detection of the volumes of all QDs measuring 2-4 nm. The result of TEM characterization suggests a homogenous spherical morphology for all the core-shell QDs samples, and their volume V_{total} can be calculated from the mean diameters. Because of the similar lattice constants between InP and ZnS and the homogeneous lattice assembly shown in the TEM image, we can calculate the volume ratio between the InP and ZnS components in the core-shell QDs using their elementary ratio (for details, see the Supporting Information). Assuming that all the ZnS is coated on the surface of InP without any alloy diffusion, the shell coverage for each sample can be estimated (for details, see the Supporting Information). Based on our calculation, because the overall ZnS amount was fixed during the synthesis, the increase in the core size of InP from 2.4 to 3.6 nm resulted in a decrease in the shell coverage from 100% to 50%, as illustrated in Figure 1c. However, we demonstrated that such a submonolayer shell coverage was sufficient to passivate the surface trap states, thus resulting in a significant improvement in the PLQY by up to 78%. (Table S3, Supporting Information).

2.2. Excitation Intensity-Dependent Excited State Dynamics

The single- and multi-exciton dynamics in the InP and InP/ZnS QDs were characterized via transient absorption (TA) spectroscopy excited at 400 nm with an excitation fluence ranging from 2×10^{13} to 7×10^{14} photons/pulse/cm² (further details are available in the Supporting Information). Figure S3, Supporting Information shows the typical pseudocolor TA spectra of both the InP and InP/ZnS QDs at a low fluence of 2×10^{13} photons/pulse/cm². These conditions correspond to a calculated average excitation number per QD <N> of less than 0.1 (for details of the exciton density see the Supporting Information). The TA spectra exhibited two prominent characteristics: a negative ground-state bleach band (GB) at ≈525 nm and a positive photoinduced absorption (PIA) band from 580 to 700 nm (Figure S3, Supporting Information). Because of the much larger bandedge density of states (DOS) and higher degeneracy degree of the valence band compared with those of the conduction band in InP, the TA signal was only sensitive to the population of



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Figure 1. Steady-state absorption (line) and photoluminescence (dotted line) spectra of a) InP QDs and b) InP/ZnS core-shell QDs. c) Schematic diagrams of InP/ZnS core-shell QDs with increased core sizes from left to right (average size shown in black font; volume shown in gray font). The coverage decreased as the core size of QDs increased (coverage ratio shown in blue font).

excited electrons in the conduction band.^[24] The nature of the PIA in QDs varies across different systems and has been previously attributed to either intraband transitions of photogenerated electrons or free/trapped holes. In terms of the InP system, a previous study demonstrated that both the GB and PIA regions in the TA spectra of InP QDs primarily originated from photogenerated electrons.^[17] The shift of the GB and PIA bands in the InP and InP/ZnS QDs with increasing particle size is associated with the narrowing of the optical bandgap, as mentioned above. We first compared the excited-state dynamics of core and core-shell QDs by examining their kinetics at the maximum TA bleach position. When <N> was well below 0.1, where no high-order recombination is expected, the GB decay lifetime of the InP/ZnS QDs was much longer than that of pure InP QDs (Figure 2a). The multi-exponential fitting of these two decays yielded two components: a fast component with a lifetime of ≈ 100 ps and a slow component with a lifetime of ≈ 10 ns (the multi-exponential fitting equation is presented in Section 7). The fast component can be attributed to the nonradiative recombination between the excited electrons and surface-trapped holes, which is consistent with the results in the literature.^[25] Notably, the initial rapid hole trapping of the surface P dangling bonds cannot be resolved via TA, as mentioned above.^[17] The slow component can be attributed to single exciton radiative recombination in the InP-based QDs without surface trapping.^[25,26] After a

ZnS shell was coated, the amplitude of the fast component decreased from 0.22 to 0.18, thus indicating surface passivation, which diminished the trapping even in the presence of submonolayer coverage. When <N> exceeded 1, multiple excitons were generated within one QD. Figure 2c shows the TA decay kinetics as a function of the excitation density of the InP500 QDs. As the excitation fluence increased (to $\langle N \rangle$ of ≈ 1 and higher), a much more rapid component occurred in the TA dynamics at an early timescale within 20 ps, which was attributed to the high-order recombination of multiple charge carriers or excitons in the QDs.^[27] Full-fitting curves were obtained using a multiexponential function, which revealed three distinct components. Notably, this rapid component, which occurred at ≈ 11 ps, is not due to the surface-trapping process with a lifetime of hundreds of picoseconds, as discussed above. The second component, which occurred at hundreds of picoseconds, comprised processes related to surface trapping. The third component, whose lifetime was in the nanosecond range, was radiative recombination. Although multi-exponential fitting is typically more suitable for analyzing single exciton recombination dynamics, the fitting results obtained for the fast component in high-order recombination offer valuable insights for the subsequent analysis of the Auger dynamics. In the InP QDs, an nonmonotonic change in the decay with increasing excitation intensity was observed, as shown in Figure 2b, where the 160 ps component first www.advancedsciencenews.com

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Figure 2. a) Comparison of bleach normalized decay kinetics of InP QDs and InP/ZnS core-shell QDs. b) Normalized decay kinetics of InP QDs at different fluences. c) Bleach decay kinetics of InP500 QDs for different excitation fluences. d) DA⁻² versus t for InP samples. e) Bleach decay kinetics of InP/ZnS500 QDs for different excitation fluences. f) DA⁻² versus t for InP/ZnS core-shell samples.

diminished from 2×10^{13} to 1×10^{14} photons/pulse/cm², followed by the appearance of fast decay component when the excitation fluence exceeded 1×10^{14} photons/pulse/cm². The initial slowdown of the TA kinetics can be attributed to trap filling to reduce the number of effective trapping centers in the excited state. This phenomenon was similarly observed in perovskite QDs.^[28] By contrast, in the core-shell QDs, such trap filling was absent, whereas only fast decay component appeared at high fluences owing to diminished surface traps (Figure 2e). The fast component appearing in both samples at a high fluence exhibited a much shorter lifetime than the time required for surface trapping. The linearity between the DA⁻² versus t relationship of the decay trends of the InP and InP/ZnS QDs at an early time scale (Figures 2d,f)) further confirmed the third-order recombination of the excited species within this time window, which is characteristic of nonradiative Auger recombination.^[29] The analyses presented above confirmed that Auger recombination occurred due to increased fluence in the InP and InP/ZnS QDs (Table 1).

2.3. Auger Recombination Time and its Volume Scaling

To extract the Auger recombination time from the TA kinetics, we normalized all the kinetic decays with different excitation fluences by their long-lived tails after 1 ns (Figure 3a). These normalized decay curves began to overlap after hundreds of picoseconds, thus indicating identical single-exciton depopulation dynamics after multi-exciton recombination (Figure 3a).^[30] According to a well-established protocol, multi-exciton dynamics can be

extracted by subtracting the decay kinetics of higher fluence levels from those of the lowest fluence level.^[31] Subsequently, the subtracted dynamics are subjected to exponential fitting to obtain the Auger recombination time. This protocol is applicable to core–shell QDs, as shown in Figure 3. However, the trapping and filling processes in InP QDs render the selection of reference kinetics challenging. As illustrated in Figure 3, we selected the TA kinetics at <N> ≈ 0.12 as the reference kinetics and subtracted all the kinetics with fluences above it by this decay because it represents the threshold where trap filling deactivates all the surface traps and the multi-excitons can be accumulated above this excitation density.

The extracted multi-exciton kinetics of the InP QDs can be fitted using bi-exponential functions. The fast components within 1 ps are attributed to the Auger biexciton lifetime τ_{xx} , whereas the slow component with a timescale of tens of picoseconds can be ascribed to the recombination of negative trion after holes are trapped to the surface states. The average biexciton lifetime

Table 1. Multi-exponential fitting of dynamics in Figure 2b with different fluences. First column represents pulse fluence (units: photons/pulse/cm²). A_i and τ_i (i = 1, 2, and 3) represent fraction and lifetime of exponential fitting results, respectively.

	A ₁	τ_1/ps	A ₂	τ_2/ps	A ₃	τ_3/ps
2 × 10 ¹³	-	-	0.22	165	0.78	11603
1×10^{14}	-	-	0.18	220	0.82	12 420
7×10^{14}	0.15	11	0.20	557	0.65	12 975

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Figure 3. Bleach decay kinetics of a) InP500 QDs and b) InP/ZnS500 as a function of excitation fluences. Kinetics of all traces are normalized at 1 ns. Kinetics at $\langle N \rangle \approx 0.02$ (green line) represents a rapid trapping process with a fast decay at an early time scale. Kinetics at $\langle N \rangle \approx 0.02$ (black line) are exempt from such a rapid trapping process due to trap filling. It is used as the baseline for subtraction by the kinetics with higher fluence. b) Biexciton lifetime of QDs as a function of volume.

obtained for InP500 was less than 1 ps, which is consistent with previously reported results for InPs with similar particle sizes.^[17] Figure 3b shows the extracted biexciton lifetime τ_{xx} as a function of the QD volume (V) for all the size-dependent InP and InP/ZnS QDs. For the pristine InP QDs, the τ_{xx} value scaled approximately linearly with V: $\tau_{xx} \propto \beta V$, in which β is the scaling coefficient with a value of 0.10 ± 0.01 ps nm⁻³. Compared with CdSe and PbSe QDs, which exhibit a scaling coefficient of ≈ 1 ps nm⁻³, the InP QDs showed a much weaker size dependence on Auger recombination.^[32] However, for halide perovskite QDs, the scaling coefficient varies depending on the halide used. Specifically, the scaling coefficient of InP was located between 0.142–0.004 and 0.085–0.009 ps nm⁻³ as the halide changed from iodide (I) to bromide (Br).^[33]

In general, for InP/ZnS QDs, the ZnS shell coating increases the biexciton lifetime, as shown in Figure 3b. This effect has been widely observed in both InP and other semiconductor QDs owing to the passivation of surface-trapping states.^[17] Despite the prolonged τ_{xx} after shell coating, previous studies indicated that the conventional V-scaling law remains valid if the shell thickness is not overly large (e.g., ML < 3).^[34] However, in our study, we observed two unconventional stages in the evolution of the biexciton lifetime as a function of volume, as shown in Figure 3b. For small-volume InP/ZnS QDs below 15 nm³, τ_{xx} was fixed at approximately 0.6 ps. When the QD volume exceeded 15 nm³, the $\tau_{\rm xx}$ increased significantly by five times to \approx 3 ps. In both stages, no clear size-dependent increase in τ_{xx} was observed. To justify the existence of the two stages, we directly compared the early time dynamics of all samples excited at the highest fluence (7 \times 10¹⁴ photons/pulse/cm²) (Figure S10, Supporting Information), where Auger recombination processes dominated. As shown in the following figure, two distinct stages can be clearly observed, where the decays of InPZnS480, 500, and 540 overlapped, as were the decays of InPZnS580 and 610.

One accepted interpretation of the effect of the shell structure on the Auger process in QDs is the modification of the Coulomb interactions between the electrons and holes through wavefunction engineering. This is achieved by inducing the spatial separation of electrons and holes, which reduces the wavefunction overlap for ground-state electrons and holes participating in the Auger recombination.^[12] However, the energy-band alignment in our InP/ZnS core-shell QDs are expected to exhibit a type-I configuration.^[35] Nonetheless, this is unlikely to occur.

In general, the nonradiative Auger recombination rate can be calculated using Fermi's Golden Rule as follows^[20]:

$$k_{\text{Auger}} = \frac{1}{\tau_{\text{Auger}}} = \frac{2\pi}{\hbar} \int \left| M_{if} \right|^2 \delta \left(E_i - E_f \right) dR_f \tag{1}$$

where M_{if} represents the electronic transition matrix element of the interparticle Coulomb interactions; E_i and E_f correspond to the initial and final energies of the system, respectively; and R_f denotes the complete set of variables that quantify the final state of the system. A significant issue in calculating the Auger rate is obtaining an accurate estimate of the transition matrix element M_{if} in Equation 1. Based on the Fourier expansion of the ground state wave functions, the leading contribution to M_{if} is expressed by the spatial frequency component, k_F , which matches the large momentum of electrons or holes in the excited final state, $k_F \approx k_f$. In heterostructures, a large k_F is typically generated when abrupt energy differences occur at the heterostructure interfaces. This directly affects the matrix element M_{if} , which consequently accelerates the rate of the Auger process.

Based on the analysis above, both the effective size and electronic band structure of the InP/ZnS core-shell QDs compete to determine the final Auger recombination rate. In pure InP QDs, the biexciton lifetime obeys the general V-scaling law, in which large QDs exhibit a low Auger rate owing to the quantum confinement effect. When ZnS is coated on the surface, the band alignment between the core and shell materials is an influential factor. QDs with larger core sizes and narrower bandgaps are likely to form deeper quantum wells. Such deep quantum wells result in a more abrupt interfacial potential contrast, thus resulting in a faster Auger process. This effect competes with the general rule of size dependence of the Auger rate in QDs, as mentioned above (i.e., the Auger recombination would be diminished in large QDs owing to reduced quantum confinement). This explains the constant Auger rates regardless of the QD size in the two separated states as a result of the tradeoff between the two opposing factors.



Figure 4. Effects of a) effective size, b) band alignment, and c) ZnS shell coating on biexciton lifetime.

However, the abrupt increase in the Auger lifetime before and after 15 nm³ is likely due to the change in the surface shell coverage, as shown in Figure 1c. When the volume is less than 15 nm³, which corresponds to the case where monolayer coverage is almost fully attained (\geq 69%), the QDs experience strong confinement with an almost complete quantum well coverage. This confinement effectively restricts the escape of the carrier wave function, thus resulting in a shorter Auger recombination time. Conversely, when the coverage exceeds 15 nm³, a submonolayer coverage is likely to form with much less confinement in the QDs. Consequently, the likelihood of carrier wavefunction leakage increases, thus resulting in a lower Auger recombination rate.

To further validate our hypothesis regarding the influential role of coverage, we investigated samples of the same core size but different forms of shell coverage. The TEM results indicated that the particle size remained at approximately 3.2 nm (Figure S8, Supporting Information). The XPS results indicated that the coverage percentage increased from 0.6 to 0.8 (Table S2, Supporting Information). The early TA kinetics of the samples at high excitation fluences (Figure S9, Supporting Information) clearly showed that the Auger recombination process accelerated as the shell coverage increased. These results further support our assumption that the abrupt transition observed between the two stages can be attributed to shell coverage. Additionally, we also noticed that the change in surface dielectric condition might induce the weakening of dielectric screening which can play the opposite role in accelerating the Auger process. The above observation indicates that the influence of the wavefunction leakage in partial shell-covered QDs in Auger recombination should be dominant.

Figure 4 summarizes the effect of quantum-well confinement, effective size, and shell coverage on the Auger recombination rate in the core–shell QDs. In Figure 4a, for the pure-core QDs, the biexciton Auger recombination reflected the universal volume scaling law, where the τ_{xx} value scaled approximately linearly with the volume. When a full-coverage monolayer ZnS shell was coated, as depicted in Figure 4b, the passivation of the surface trap states resulted in a higher PLQY. In fact, this passivation of trap states decelerated the Auger recombination process. As the QD core size increased, two factors were involved and competed with each other: the reduced quantum confinement in large QDs decreased the wavefunction overlap between the two excitons, thus resulting in a lower Auger rate. However, the

deepened core–shell quantum well, accompanied by a decrease in the bandgap of the cores, enhanced the Auger processes. Consequently, a constant Auger rate was observed. Moreover, as the core size increased, the surface coverage of the shell materials shifted from a monolayer to a submonolayer, thus resulting in an abrupt change in quantum confinement. This contributed to the abrupt increase in the biexciton lifetime observed before and after a volume of 15 nm³ was attained.

The ultimate objective of passivating surface trap states and suppressing the recombination rate is to facilitate electron injection.^[37] However, for future device designs, employing the full coverage of InP/ZnS core-shell QDs is not ideal for electron injection. This is because the electrons in the core must overcome the energy barriers arising from the large bandgap and the positions of the valence band maximum and conduction band minimum.^[38] The ideal design, as depicted in Figure 4c, involves a quasi-monolayer ZnS shell coated on the InP core QDs. In the InP/ZnS 580 sample, this quasi-monolayer ZnS shell effectively passivated the surface trapping states, thus resulting in an increase in the PLQY from 5.2% for the InP core QDs to 42.5% for the InP/ZnS core-shell QDs. We conclude that such discontinuous coverage of the shell reduces quantum confinement, thus resulting in a significant increase in the biexciton lifetime. In fact, for similar volumes of QDs, the biexciton lifetime was more than doubled.

3. Conclusion

In this study, size-dependent Auger recombination rates in InP and InP/ZnS QDs were investigated using transient absorption spectroscopy. For pure InP-core QDs, the Auger recombination rate reflected the universal volume scaling law, where the biexciton lifetimes scaled linearly with the QD volume. For the InP/ZnS core-shell QDs, the ZnS shell not only passivated the surface trap states, but also prolonged the Auger lifetime. The QD biexciton lifetimes were almost constant with the QD volume below and above 15nm³ but changed abruptly between these two regions. This is due to the competing effects among the core size, core-shell quantum well confinement, and surface shell coverage, which affected the quantum confinement in QDs. This study provides a reference for utilizing core-shell QDs and surface coatings to design high-efficiency devices for surface-trapping passivation, Auger recombination suppression, and electron injection.

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Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

auger recombination, biexciton, indium phosphide, quantum dots, submonolaver

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