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**Citation:** Chen, Ou, Jing Zhao, Vikash P. Chauhan, Jian Cui, Cliff Wong, Daniel K. Harris, He Wei, et al. "Compact high-quality CdSe–CdS core–shell nanocrystals with narrow emission linewidths and suppressed blinking." *Nature Materials* 12, no. 5 (February 3, 2013): 445-451.

**As Published:** <http://dx.doi.org/10.1038/nmat3539>

**Publisher:** Nature Publishing Group

**Persistent URL:** <http://hdl.handle.net/1721.1/84084>

**Version:** Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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## **Compact high-quality CdSe/CdS core/shell nanocrystals with narrow emission linewidths and suppressed blinking**

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### **Abstract**

High particle uniformity, high photoluminescence quantum yields, narrow and symmetric emission spectral lineshapes and minimal single dot emission intermittency (known as blinking) have been recognized as universal requirements for the successful use of colloidal quantum dots (QDs) in nearly all optical applications. However, synthesizing samples that simultaneously meet all these four criteria has proven challenging. Here, we report the synthesis of such high-quality CdSe/CdS core/shell QDs in an optimized process which maintains a slow growth rate of the shell through the use of octanethiol and cadmium oleate as precursors. In contrast with previous observations, single-QD blinking is significantly suppressed with only a relatively thin shell. In addition, we demonstrate the elimination of the ensemble luminescence photodarkening that is an intrinsic consequence of QD blinking statistical aging. Furthermore, the small size and high photoluminescence quantum yields of these novel QDs render them superior *in vivo* imaging agents compared to conventional QDs. We anticipate that this new generation of QDs will also result in significant improvement in the performance of QDs in other applications such as solid-state lighting and illumination.

Nanocrystal quantum dots (QDs) have great potential as a unique optical material in a broad range of applications that rely on downshifting light, especially those relying on achieving spectral purity at high optical flux. These applications include multiplexed labelling and tracking of cells or molecules in a biological environment<sup>1-4</sup>, downshifting light for colour engineering in solid-state lighting, illumination and displays<sup>5-7</sup>, and single-photon sources<sup>8-10</sup>. In order to fully realize the potential of QDs in this broad class of applications, the following major criteria, which may not be strictly independent, need to be simultaneously fulfilled: 1) high particle uniformity, 2) high photoluminescence quantum yields (PL QYs) for optimized brightness, 3) narrow and symmetric emission spectra for multiplexing and/or color saturation, 4) minimized single-QDs blinking for tracking and/or for light output stability. In addition, applications in biological environments generally require the QDs to be as compact as possible to minimize interactions with biological systems and to maximize diffusion to confined biological spaces of interests<sup>11</sup>.

In the past two decades, great progress has been made in synthesizing QDs with uniform size, high PL QYs and narrow emission spectra<sup>12, 13</sup>. However, these QDs universally show significant “blinking”, whereby the photoluminescence of single-QDs turns “on” and “off” under continuous excitation, which limits the use of QDs in tracking applications, as single-photon sources and in downshifting illumination applications at relatively high fluxes<sup>14-16</sup>. Recently, a few groups have reported successes toward non-blinking or nearly non-blinking QDs<sup>17-22</sup>. To date, two general approaches have been developed towards suppressing blinking. The first approach relies on changing the solution environment of the QDs by adding “antiblinking agents” that presumably bind to the QD surface<sup>17-19</sup>. However, this blinking suppression is not an intrinsic property of the QDs and relies on weakly bound surface species so that the initial blinking state is easily and almost immediately recovered by displacement of the “antiblinking agent”<sup>17, 18</sup>. This lack of robustness and the requirement

of the QDs being in a solution containing an excess of the “antiblinking agent” are unacceptable for most applications<sup>1-4</sup>. The second approach is to grow a thick inorganic shell (>5nm) on the QDs in order to fully isolate the excited carriers from the QD surface and the surface environment<sup>20, 21</sup>. However, these “giant” core/shell QDs are often large, with a poor size distribution, have a broad PL spectra, with only moderate ensemble PL QYs<sup>20, 21</sup>. Therefore, synthesizing QDs that simultaneously satisfy all criteria discussed above has not yet been possible.

We have met the challenge here through a novel synthesis that produces high-quality CdSe/CdS core/shell QDs using cadmium (II) oleate (Cd-oleate) and octanethiol as shell precursors. Due to the strong carbon-sulphur chemical bond in octanethiol, the shell-growth temperature is at 310 °C. The slow continuous shell precursor infusion and the relatively low reactivity of octanethiol provide an optimal condition, leading to a well-maintained particle size distribution during shell growth. Because of the small lattice mismatch (3.9%) between core and shell and the slow, high temperature growth, the resulting QDs maintain the original crystal structure of the CdSe core. In contrast with previous observations, we find that single-QDs blinking is significantly suppressed with only a relatively thin shell (~2.4nm, ~7 monolayers (MLs)). Consequently, the intrinsic ensemble PL photodarkening induced by blinking statistical aging is eliminated, making these QDs stable ensemble PL output sources even at relatively high optical fluxes. Most importantly, this new generation of QDs for the first time simultaneously satisfies the four criteria of high uniformity, high PL QYs (up to 97%), narrow PL peaks (full width at half maximum (FWHM) as narrow as 67.1meV (~20nm)), and significantly suppressed blinking (~94% average on-time fractions). Additionally, this thin shell allows for compact QDs suitable for biological imaging applications. These QDs can be easily brought into water maintaining the high PL QYs (>70%) desired for imaging probes in highly scattering biological environments. This new generation of QDs will result in significant performance improvements in a variety of applications

ranging from solid-state lighting, illumination and displays to biological multiplexed labelling and tracking.

Absorption and PL spectra of four CdSe/CdS QDs samples synthesized by our method are shown in Fig. 1a-d. Cd-oleate and octanethiol were chosen as the shell precursors. The low reactivity induced by the strong carbon-sulphur covalent bond in octanethiol requires a relatively high temperature (310 °C) for shell growth. During the overcoating reaction (Supplementary Information), both the PL peak and the absorption features shift to lower energy (Fig. 1e,f) as a consequence of the weak exciton confinement generated by the CdS shell<sup>23</sup>. Narrow and symmetric PL peaks and absorption spectra with well-resolved transitions indicate that particle size distributions remain tight throughout the entire shell-growth process (Fig. 1e,f). PL QY measurements show that after an initial drop, due to quenching by the addition of octanethiol (Fig. 1g),<sup>24, 25</sup> the PL QY monotonically increases during the reaction and reaches its maximum when the reaction solution is annealed at 310 °C for 60 min following precursors injection (Fig.1g). The PL QYs of the obtained QDs were observed to be as high as 97%. The PL peak FWHM decreases dramatically from 96.2 meV for “bare” CdSe QDs to 67.1 meV (~20 nm) for final CdSe/CdS QDs (Fig. 1h), consistent with the decreased half width at half maximum of the first absorption peak (Fig. S3). Remarkably, this uniquely narrow ensemble PL peak width (67.1 meV) is comparable to that from single-QDs (50~70 meV)<sup>26</sup>. To the best of our knowledge, such a narrow and symmetric ensemble emission peak has not been achieved before for any CdSe based core/shell or alloy QDs. This narrow ensemble PL can enhance the spectral purity of QD based illumination or display applications, and enables an increased number of wavelength detection channels in multiplexing applications.

Transmission electron microscopy (TEM) measurements show that, during CdS shell growth, the average particle diameter increases from 4.4 nm to 9.1nm, which corresponds to a shell thickness of 2.4 nm (~7 MLs) (Fig. 2a-d, Fig. S5)<sup>27</sup>. The size distribution of the core/shell QDs remains exceptionally

narrow ( $\sim 4\%$ ) during the entire shell-growth process (Fig. 2a-d, Fig. S5), consistent with optical measurements (Fig. 1). This narrow size distribution may be due to the slow shell precursor infusion and the low reactivity of the octanethiol which may provide a constant and sufficient monomer production rate, consistent with a recent model<sup>28</sup>. Energy dispersive X-ray spectroscopy shows that the atomic percentages of Cd, Se and S atoms are in good agreement with the calculated values based on the CdSe core size and CdS shell thickness determined by TEM (Fig. 2e). High-Resolution TEM images reveal high crystallinity with lattice fringes throughout the whole particle (Fig. 2f inset, Fig. S7). The displayed lattice distance of 3.64 Å (Fig. 2f inset) corresponds to the (100) lattice spacing of the wurtzite (W) crystal structure. XRD results confirm a W crystal structure with characteristic (102) and (103) Bragg peaks (Fig. 2f), in agreement with the W crystal structure of the starting cores, demonstrating epitaxial shell formation. To further confirm this epitaxial shell growth, W-CdSe cores were replaced with zinc-blende (ZB) CdSe cores. As expected, the resulting particles show a ZB crystal structure (Fig. S8)<sup>29</sup>. This observation is in contradiction with recent results that the CdS shell growth on ZB-CdSe QDs in the presence of primary amines (i.e., oleylamine) necessarily generates core/shell particles simultaneously containing both W and ZB crystal structures<sup>20, 30</sup>. We believe that in our case, the slow shell growth maintains the original crystal structure of the starting core material. Moreover, these results are in accordance with the recent finding of ZB-CdSe/CdSe iso-material core/shell growth<sup>31</sup>.

As shown in Fig. 1, the PL peak of the final core/shell QDs is remarkably narrow (FWHM: 67.1 meV,  $\sim 20$  nm), comparable to single-QDs emission linewidths<sup>26</sup>. Such uniquely narrow and symmetric ensemble emission peaks are desired in many applications. Exploring the origins of this narrow emission peak is therefore intriguing.

We can consider two possible scenarios: (i) The average PL peak width of single-QDs synthesized here is narrower than that of single-QDs synthesized by other methods, resulting in a

narrower ensemble PL peak, or (ii) the narrow ensemble emission peak comes from the high sample uniformity, minimizing inhomogeneous broadening from size/morphology distributions. To examine these hypotheses, we carried out emission linewidth measurements for single-QDs as well as for the ensemble using Photon Correlation Fourier Spectroscopy in solution (S-PCFS)<sup>32, 33</sup>. The average single-QDs and ensemble spectral correlations for our core/shell QDs are shown in Fig. 3a. After fitting (Supplementary Information), the ensemble emission FWHM is 69 meV, nearly identical to that obtained using a spectrometer (Fig. 1e,h). The average single-QDs emission FWHM is 63 meV, in good agreement with previous studies<sup>26, 32</sup>. The small difference (6 meV, ~10%) between the single-QDs and the ensemble emission linewidths indicates extremely high uniformity of the sample including uniform shape, narrow size distribution, high shell crystallinity, sufficient surface passivation, etc. These results confirm the hypothesis of scenario (ii) that this narrow ensemble PL peak is due to the high uniformity of our QDs, rather than unusually narrow single-QDs PL peaks [scenario (i)].

For comparison, the emission linewidth of the CdSe/CdS QDs synthesized using a conventional method<sup>34</sup> was also measured using S-PCFS (Fig. 3b). Fitting results show that the average single-QDs emission FWHM is 65 meV. However, the ensemble emission linewidth is 111 meV (~34 nm), ~60% broader than our QDs, indicating a relatively polydisperse sample. TEM measurements show two indications of increased polydispersity: broader particle size distribution (~6%) and irregular shapes (Fig. S10). Other factors not observed in TEM, such as a polydispersity in surface structure, insufficient surface passivation, and increased spectral diffusion may also be contributing factors to this broader ensemble linewidth.

Ever since single-QDs fluorescence intermittency has been discovered<sup>14-16, 35, 36</sup>, it has been recognized as a potential limitation of QDs in a variety of applications. For example, the existence of long “off” periods (e.g., tens of seconds or longer) hinders the use of QDs in biological settings for

tracking. Blinking also limits the potential use of QDs as single-photon sources. In another example, the power-law distribution associated with “off” times at the single-QDs level results in an intrinsic ensemble PL photodarkening when the dots are continuously excited with high flux<sup>37, 38</sup>. This intrinsic photodarkening limits QDs from being a stable PL output source under high flux excitation, such as in solid-state lighting and low-threshold lasers. QDs with suppressed blinking are therefore attractive across a broad class of applications.

To further characterize our QDs at the single-emitter level, we studied single-QDs blinking behaviour using a CdSe/CdS QDs sample with a shell thickness of 2.4 nm (~7ML). Fig. 4a shows a representative PL blinking trace and histogram of PL intensity distributions. The antibunching dip ( $\tau = 0$ ) from a second-order photon intensity correlation ( $g^{(2)}(\tau)$ ) measurement is consistent with the expected emission from a single-QD and not a cluster of QDs (Fig. S11)<sup>39</sup>. Some antibunching “dips” do not drop to the background level (Fig. S13), due to the heterogeneity of bi-exciton (BX) QYs recently observed<sup>39-41</sup>. This heterogeneity in BX QYs does not affect our observed blinking traces because of the negligible BX population under our experimental conditions<sup>39</sup>. Figure 4a shows well-resolved “on” –“off” blinking. An average time fraction that the QDs stay “on” during the course of the measurements was extracted from 135 blinking traces each from a different QD, with the resulting distribution shown in Fig. 4b. The average “on” fraction is ~94% and ~20% of the QDs we studied displayed an on-time fraction greater than 99% (Fig. 4b). Note that “grey states” which have been observed and attributed to the emission from a positive trion have not been observed here<sup>42</sup>. This indicates that deep electron or hole traps are significantly eliminated, consistent with the high on-time fraction measured for exciton emission.

The statistics of “on” and “off” times calculated from the blinking traces are plotted in Fig. 4c. The probability distributions for the duration of “on” and “off” events,  $P_{on/off}$ , fit power-law distributions ( $P_{on/off}(t_{on/off}) \propto t^{-\alpha_{on/off}}$ ) where  $t_{on/off}$  are the time intervals for a QD in an “on” or



“off” state, and  $\alpha_{on/off}$  are the power-law exponents expressing the statistics of “on”/“off” events. For our core/shell QDs,  $\alpha_{on} = 0.85$  and  $\alpha_{off} = 2.2$ . Note that usually both  $\alpha$  values for CdSe/ZnS QDs are close to 1.5<sup>16, 37, 38, 43, 44</sup>. The slow decay of the on-time distribution and fast decay of the off-time distribution indicate that PL blinking is dominated by long “on” events and short “off” events, consistent with the observed high on-time fraction. These exponents describe distributions of “on” and “off” times that are qualitatively different from the usual ones, and as discussed below, predict an ensemble behaviour that is also qualitatively different.

Recent work shows that the blinking of CdSe/CdS QDs can be dramatically suppressed by growing thick CdS shells (>5nm, ~15 MLs), which effectively isolate the excited carriers from the nanocrystal surface and surrounding environment<sup>20, 21</sup>. Recently, Ghosh et al. correlated single-QDs blinking suppression with particle volume<sup>45</sup>. They claim that in order to observe suppressed blinking from single CdSe/CdS QDs, the final single particle volume must be no less than  $\sim 750 \text{ nm}^3$ , with a radiative lifetime of  $\sim 65 \text{ ns}$  or longer<sup>45</sup>. However, the single-particle volume of our QDs is only about half of their threshold volume ( $\sim 390 \text{ nm}^3$ ) with a much shorter PL lifetime of  $\sim 32 \text{ ns}$  (Fig. S12). Our results strongly suggest that, even with a relatively thin shell, the blinking behaviour of core/shell QDs can be qualitatively altered by improved synthetic methodology. We speculate that the significantly reduced blinking observed here is at least partially caused by a highly crystalline shell that results from high-temperature slow shell-growth conditions.

To prove this hypothesis, we synthesized CdSe/CdS QDs with a very thin shell ( $\sim 0.7 \text{ nm}$ ,  $\sim 2$  MLs) through our method and characterized their blinking properties. The calculated on-time fraction of 85% (Fig. 4d and Fig. S14) is dramatically higher than that of CdSe/CdS QDs with similar shell thickness synthesized using more common methods<sup>20, 45-47</sup>. Due to this thin shell and small conduction bands offset (0.29 eV) between the core and shell<sup>48</sup>, the excited carrier (i.e., electron) is delocalized in

the entire particle and easily access the particle surface. Thus, the dramatically increased on-time fraction we observe for this sample cannot be explained by the physical separation between the excited carriers and the nanocrystal surface and surrounding environment as is usually the case for thick shell (> 5 nm) QDs<sup>20, 21</sup>. Therefore, we speculate that this improvement in blinking behaviour is a consequence of the high shell crystallinity that results through controllable and relatively slow CdS epitaxial shell formation. The use of the relatively stable octanethiol precursor provides shell precursor atoms at a slow growth rate, allowing for annealing of the shell structure and the surface during growth, minimizing defects at interfaces, within the shell and on the surface (e.g., stacking faults, vacancies, dislocation, dangling bonds etc.) which could initiate fast non-radiative decays and turn the particle “off”<sup>14, 15, 20, 21, 35</sup>. This explanation is consistent with the crystal structure study discussed above as well as the ligand-exchange results shown below. In addition, our results also demonstrate that shell thickness still does play a role in controlling single-QDs blinking, consistent with previous observations<sup>20, 45, 46</sup>, but with a significantly thinner shell.

Photodarkening effects from collections of QDs (the ensemble level) that are exclusively caused by statistical aging from single-QDs blinking have been both experimentally observed and theoretically modelled<sup>37, 38</sup>. In contrast to photochemical degradation (e.g., permanent photochemical darkening), this ensemble PL intensity decay is intrinsic, inevitable, and reversible because it is purely induced by the non-ergodicity of single-QDs blinking distributions, as expected from Lévy statistics, where the mean and variance of the distributions diverge<sup>49</sup>. When “on” and “off” events share the same or similar power-law distributions, as is the usual case, but with the on-time distribution truncated, as time progresses, long “off” states become dominant and the ensemble PL decays. However, the QDs studied here display a qualitatively and statistically different blinking behaviour with significantly different “on” and “off” powers (0.85 vs 2.2) (Fig. 4c), compared to the usual observations where both “on” and “off” powers are

close to  $\sim 1.5$  with a short “on” time cut-off<sup>37,38</sup>. Rather than being dominated by the “off” times, as is traditionally the case, our samples are now dominated by the “on” times with significant implication for ensemble PL stabilities. To explore the PL stability of our novel QDs at the ensemble level, a collection of QDs was excited by a continuous wave laser at 514 nm under the same excitation flux as used for previous single-QDs blinking studies (i.e., 80 W/cm<sup>2</sup>). After slightly photobrightening (PL intensity increases  $\sim 8\%$ , Fig. 4e), the PL intensity stays constant during the course of the measurement ( $\sim 7.2 \times 10^4$  s). This observation is consistent with the fast decay of the off-time distribution, the slow decay of the on-time distribution (Fig. 4c) as well as the calculation of the on-time distribution dominated ensemble PL QYs evolution (Supplementary Information). A cut-off time for this on-time distribution, which may not be easily accessible even for the measurement at ensemble level (Fig. 4e), is very likely to exist. As a control experiment, the ensemble PL intensity trace collected from a collection of CdSe/CdS QDs that were synthesized through a more conventional method with “normal” power-law blinking behaviour (Fig. S16) is plotted in Figure 4d. It reveals that after an initial photobrightening process, the ensemble PL intensity begins to decrease after  $\sim 2 \times 10^4$  s, implying a truncation of the on-time distribution at  $\sim 2 \times 10^4$  s, (a time scale inaccessible with single-QDs measurements) (Fig. S16)<sup>38</sup>. The PL intensity decreases  $\sim 23\%$  from its highest value under continuous excitation of  $\sim 5 \times 10^4$  s (Fig. 4f). These results are in good agreement with previous observations<sup>37,38</sup>. Complete PL recovery after removal of the excitation (Fig. 4f inset) is consistent with this photodarkening originating from single-QDs blinking statistical aging, and not an irreversible photochemical degradation process<sup>37,38</sup>. This result is also consistent with an initial photobrightening process that is irreversible and likely caused by neutralizing initially charged QDs as has been previously observed<sup>50</sup>.

Fluorescent organic dyes are commonly used for both *in vitro* assay detections and *in vivo* imaging applications<sup>51</sup>; nonetheless, their intrinsic characteristics of broad/asymmetric emission profiles,

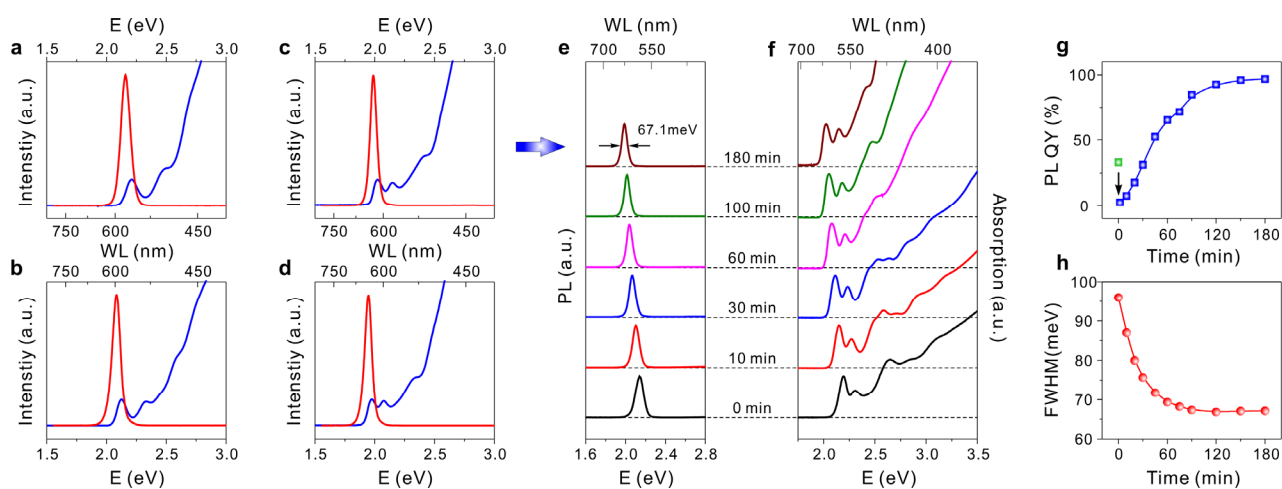
significant blinking, low absorption cross sections, and low photobleaching thresholds limit their performance in long-term and/or multiplexing imaging studies<sup>3, 4, 8</sup>. The QDs presented here with high PL QYs, narrow emission peak and suppressed blinking, render them ideal for ultrasensitive and multiplexing investigations in the broad biomedical domain<sup>3, 8</sup>. Furthermore, in an advance over prior non-blinking QDs<sup>20, 21</sup>, our new generation (ng) QDs are small and compact, which allows them to be accessible to confined biological spaces of interest<sup>11</sup>. To demonstrate the benefit of using our QDs for *in vivo* imaging, two samples underwent the same ligand-exchange reaction (supplementary information): (1) conventional CdSe/CdS QDs (QD<sub>conv.</sub>) with a PL QY of 43%; (2) our new generation CdSe/CdS QDs (QD<sub>ng</sub>) with a PL QY of 94%. Both samples were successfully transferred into aqueous solution *via* ligand-exchange reaction with methoxy-polyethylene-glycol thiol (PEG-SH, MW5000). Hydrodynamic diameters for PEG-SH capped QD<sub>conv.</sub> (QD<sub>conv.</sub>-SH-PEG) and QD<sub>ng</sub> (QD<sub>ng</sub>-SH-PEG) are 18.3 nm and 18.7 nm, respectively (Fig. S17), indicating no measureable aggregation<sup>11</sup>. After ligand-exchange, the PL QY decreased to 13% (~70% quenching) for QD<sub>conv.</sub>-SH-PEG, and to 71% (~24% quenching) for QD<sub>ng</sub>-SH-PEG (Fig. 5a and b). Thiol groups have been shown to generally quench the PL through QD surface trap states<sup>24, 25</sup>. The different PL QYs quenching levels between these two samples reflect a qualitative difference in surface passivation. Our QDs (QD<sub>ng</sub>) showed dramatically less quenching, suggesting better passivation.

To demonstrate the consequence of this improvement, we imaged QD<sub>conv.</sub>-SH-PEG and QD<sub>ng</sub>-SH-PEG *in vivo*. We intravenously injected these QDs at equal concentrations (2.5  $\mu$ M) into Tie2-GFP transgenic mice bearing dorsal skinfold chambers, and carried out intravital multiphoton microscopy in the skin (Fig. 5d, e)<sup>52</sup>. The *in vivo* fluorescence signal of QD<sub>ng</sub>-SH-PEG was ~4.7 times more intense than that of QD<sub>conv.</sub>-SH-PEG (Fig. 5d, e, Fig. S18). Importantly, these results roughly matched the

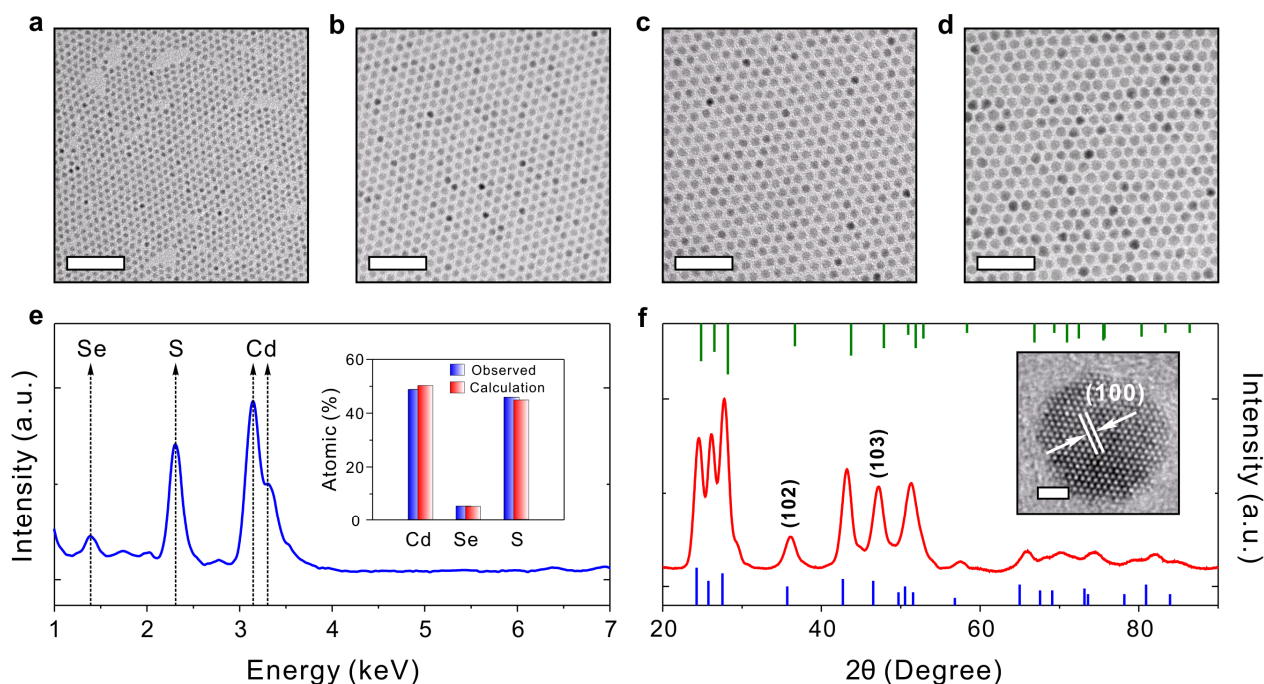
difference in QYs for these QDs (Fig. 5a, b), indicating this improved PL QYs translates to enhanced brightness for *in vivo* imaging applications.

Furthermore, similar to what we observed before<sup>11, 53</sup>, polymeric imidazole ligands (PILs) capped QDs (QD<sub>ng</sub>-PIL) show a smaller hydrodynamic diameter (~15.6 nm) (Fig. S17), higher PL QY in PBS (77%) (Fig. 5c) and brighter in *in vivo* imaging (~20% more intense) (Fig. 5f, Fig. S18) than using QD<sub>ng</sub>-SH-PEG under the same experimental conditions.

In summary, we have successfully synthesized high-quality CdSe/CdS core/shell QDs using Cd-oleate and octanethiol as shell precursors at a relatively high temperature of 310 °C. We find that, for our core/shell QDs with only a relatively thin shell (~2.4nm), blinking from single-QDs is significantly suppressed. Consequently, the intrinsic ensemble PL photodarkening induced by statistical aging from blinking under long time excitation is eliminated. Most importantly, these core/shell QDs for the first time simultaneously satisfy all four criteria including high uniformity, high PL QYs, narrow emission peaks, and significantly suppressed blinking. In addition, the relatively thin shell allows for compact QDs generally suitable for biological applications. We demonstrate that these core/shell QDs can be easily solubilized into water with high PL QYs, rendering them promising for *in vivo* imaging. We anticipate that this new generation of QDs will result in significant improvements in a variety of applications ranging from solid-state lighting and illumination under high and/or long time flux and single-photon generation, to biological multiplexed labelling, real-time tracking and *in vivo* transport studies.

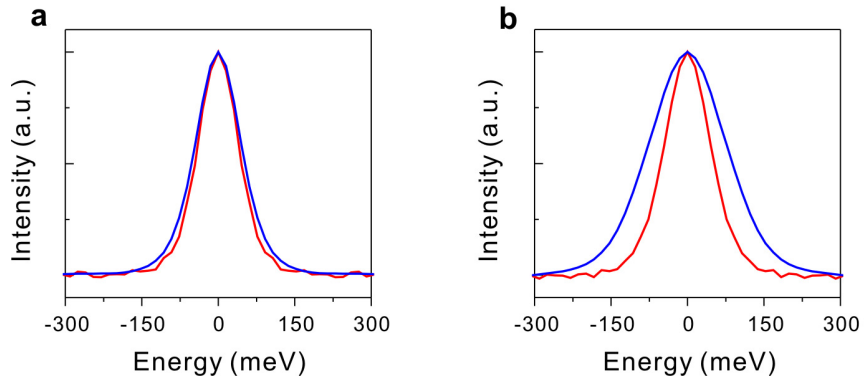


**Figure 1. Optical properties of new generation CdSe/CdS core/shell QDs.** a-d, Absorption (blue) and photoluminescence (PL) (red) spectra of four different CdSe/CdS core/shell QDs synthesized with different CdSe core diameters of **a**, 2.7 nm, **b**, 3.4 nm, **c**, 4.4 nm and **d**, 5.4 nm. Temporal evolution of **e**, photoluminescence (PL), **f**, absorption, **g**, PL quantum yields (QYs), green square shows the original PL QY of CdSe QDs, and **h**, full width at half-maximum (FWHM) of the PL peak of the CdSe/CdS core/shell QDs (shown in panel **c**) during the shell growth reaction.



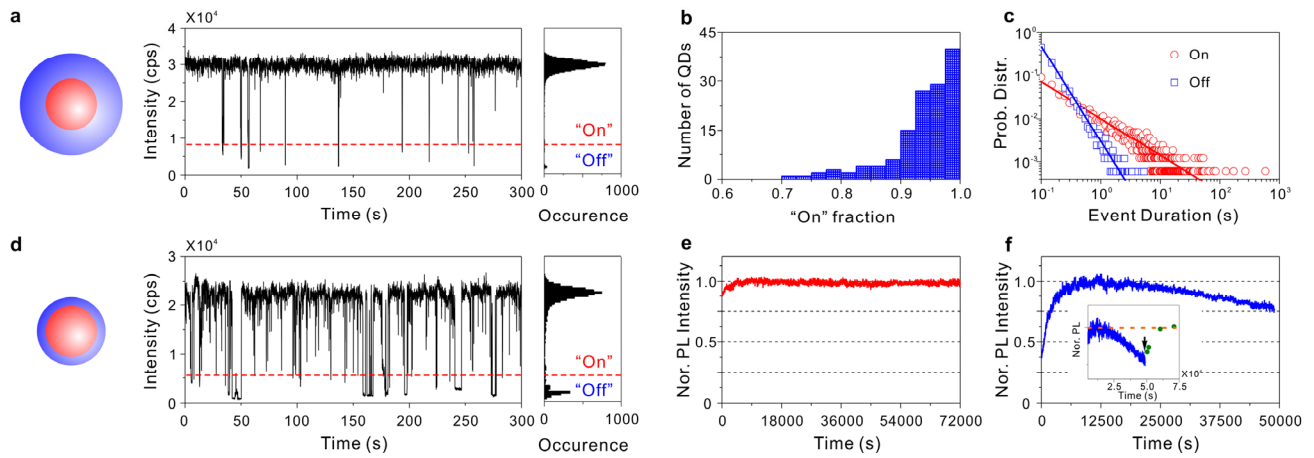
**Figure 2. Morphology, composition and crystal structure characterization of new generation QDs.**

TEM images of **a**, 4.4 nm CdSe core and **b-d**, CdSe/CdS core/shell QDs with a CdS shell thickness of 0.8nm, 1.6nm and 2.4nm, respectively. **e**, Energy dispersive X-ray spectrum of the final CdSe/CdS core/shell QDs shown in panel **d**. Inset shows the observed and calculated atomic percentages of Cd, Se and S atoms. **f**, X-ray powder diffraction pattern measured from the same sample shown in panel **d**. The stick patterns show the standard peak positions of bulk wurtzite CdSe (bottom blue sticks) and CdS (top green sticks). The inset shows a representative high-resolution TEM image of a CdSe/CdS QD. Scale bars are 50nm in **a-d** and 2nm in the inset of **f**.

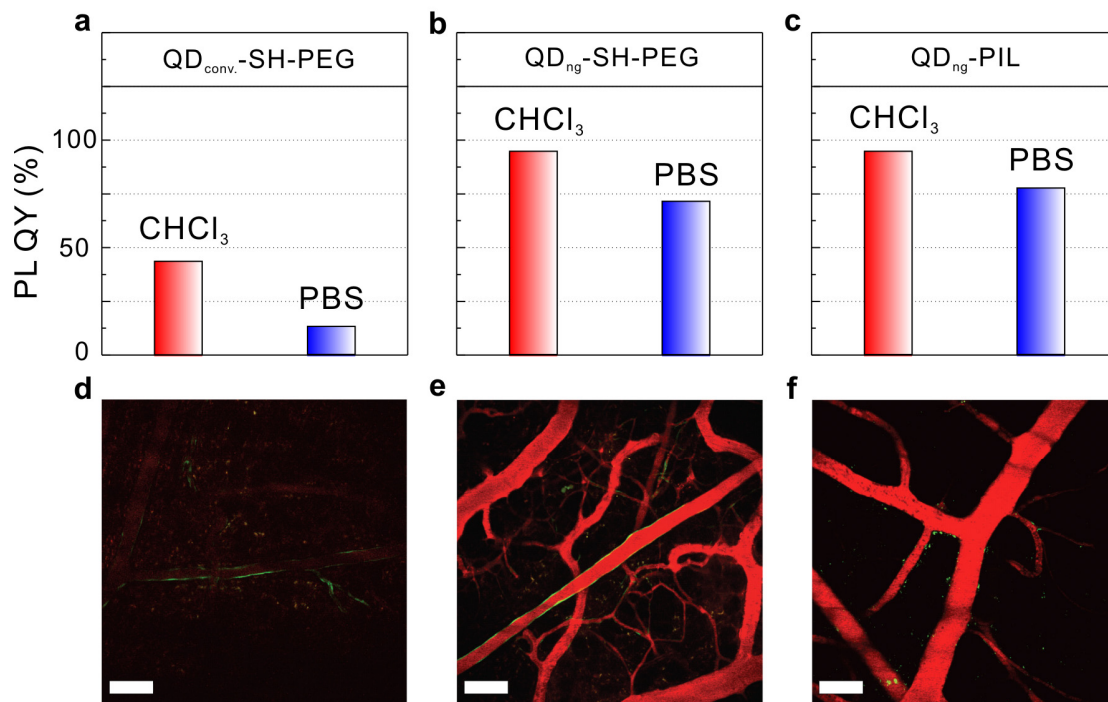


**Figure 3. PL spectral correlation of single and ensemble QDs obtained through S-PCFS.** The spectral correlations of the single QD (red line) and the ensemble (blue line) spectrum obtained by S-PCFS for CdSe/CdS core/shell QDs synthesized by **a**, our method and **b** conventional method with nearly the same shell thickness ( $\sim 7$ MLs).





**Figure 4. Blinking behaviour of new generation CdSe/CdS core/shell QDs and ensemble PL stability test.** **a**, Representative PL blinking trace of a single CdSe/CdS core/shell QD with a CdSe core radius of 2.2 nm and a shell thickness of 2.4 nm (~7 MLs) (bin size is 50 ms). Histograms indicate the distribution of intensities observed in the trace. The dashed red line indicates the value chosen as the threshold between “on” and “off” states in calculating the “on” time fraction. **b**, Histogram of the blinking “on” time fraction. The average “on” time fraction is 0.94 with a standard deviation of  $\pm 0.06$ . **c**, Log-log plot of the probability distributions of “on” and “off” times. Straight lines represent a power-law fitting using the equation  $P_{on/off}(t_{on/off}) \propto t^{-\alpha_{on/off}}$  where  $\alpha_{on} = 0.85$  for “on” times (red line) and  $\alpha_{off} = 2.2$  for “off” times (blue line). **d**, Representative PL blinking trace of a single CdSe/CdS core/shell QD with a CdSe core radius of 2.2 nm and a shell thickness of 0.7 nm (~2 MLs) (bin size is 50 ms). The PL intensity traces obtained from a collection of QDs synthesized through **e**, our new method and **f**, the conventional method. The inset in **f** shows the PL intensity recovery after an initial decay. The black arrow indicates the time point when continuous excitation was stopped.



**Figure 5. Water-soluble CdSe/CdS core/shell QDs for *in vivo* imaging.** a-c PL QYs of CdSe/CdS core/shell QDs before ligand exchange in chloroform (CHCl<sub>3</sub>) and after ligand exchange in phosphate buffer saline (PBS 1X, pH 7.4). Equal amount of these QDs (2.5 μM, 200 μL) were injected retro-orbitally into Tie2-GFP transgenic mice bearing dorsal skinfold chambers, and carried out intravital multiphoton microscopy in the skin at 30 min after injection. a and d: conventional CdSe/CdS QDs synthesized by a literature method and ligand exchanged with methoxy-polyethylene-glycol thiol (QD<sub>conv.</sub>-SH-PEG). b and e: new generation (ng) CdSe/CdS QDs synthesized by our novel method and ligand exchanged with methoxy-polyethylene-glycol thiol (QD<sub>ng</sub>-SH-PEG). c and f: new generation CdSe/CdS QDs and ligand exchanged with polymeric imidazole ligands (QD<sub>ng</sub>-PIL). In d-f, all the images are scaled to the same contrast, and scale bars are 100 μm.

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## Acknowledgements

The work received support from the NIH through grants 5-U54-CA119349 (M.G.B.) and 5R01CA126642 (M.G.B., D.F., R. J.), the ARO through the Institute for Soldier Nanotechnologies (W911NF-07-D-0004), and the NSF through a Collaborative Research in Chemistry Program (CHE-0714189) (M.G.B.). This work made use of the MRSEC Shared Experimental Facilities at MIT, supported by the National Science Foundation under award number DMR-08-19762 and the MIT DCIF NMR spectrometer funded through National Science Foundation Grants CHE-9808061 and DBI-9729592.

## Author contributions

OC and MGB conceived and designed the project. OC performed the bulk of the experimental work with help from JZ, VPC, JC, CW, DKH, HW and HSH. The data was analysed by OC, JZ, VPC, JC, CW and MGB. All authors discussed the results and took part in producing the manuscript.

**Additional information**

The authors declare no competing financial interests.

Supplementary information accompanies this paper.