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Linker-Free Modification of TiO₂ Nanorods with PbSe Nanocrystals

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We report on a colloidal synthesis of PbSe/TiO₂ heterostructures, comprising small-diameter PbSe nanocrystals epitaxially grown onto the surface of TiO₂ nanorods. The deposition of lead selenide onto prefabricated TiO₂ nanocrystals proceeds via formation of a thin PbSe shell that subsequently breaks into sub-2-nm islands. Additional precursor injections are then used to increase the size of PbSe nanocrystals up to 5 nm. In the case of small-size PbSe, a 2.1-ns transfer of photoinduced carriers into TiO₂ domain was evidenced through quenching of the PbSe band gap emission. Overall, the present synthesis demonstrates a colloidal approach to all-inorganic modification of TiO₂ surfaces with semiconductor nanocrystals, which provides a viable alternative to a more common supramolecular assembly of nanocrystal-oxide composites.

1. Introduction

Titanium dioxide is an important photovoltaic and photocatalytic material,¹ which utilization in dye-sensitized solar cells,² and hydrogen production³ is encouraged by its low fabrication costs and minimal environmental hazards. Efficient harvesting of solar radiation within TiO₂ generally requires extending its absorption range into the visible and near-infrared range by introducing an appropriate sensitizer that engages in an electron-transfer reaction with an oxide material upon receiving a photon of light. To date, the most common strategy for the sensitization of TiO₂ involves modification of its surface with organic-based transition-metal complexes, such as porphyrins⁴ or Ru complexes.² However, incorporation of semiconductor nanocrystals (NC) as sensitizers is now being actively explored⁵–²⁰ because of a number of advantages offered by inorganic NCs, including wider absorption profile, superior resistance to photobleaching, and continuous tunability of NC conduction levels.

As shown by recent reports, successful modification of anatase TiO₂ or amorphous TiO₂ with colloidal CdSe,¹² InAs,²¹ PbSe,²² and PbS²³ NCs can be achieved in a reproducible manner, leading to heterostructures that exhibit photoinduced charge separation. In these works, however, deposition of colloidal nanocrystals onto the oxide material still relies on organic linkers or nonepitaxial contacts with NC ligands,²² which makes it difficult to extract photoinduced carriers from NC domains, leading to the decrease in electron-transfer rates and carrier trapping at hybrid interfaces. For instance, surprisingly slow photoinduced electron transfer has been reported in organically coupled PbS–TiO₂ systems.²² To avoid these problems, several groups have attempted in situ growth of CdS²²–²⁶ NCs onto mesoporous TiO₂ films in ionic solutions. Although the observation of the 2–3-fold increase in the solar conversion efficiency of such films was encouraging, the quality and size distribution of NCs fabricated using this approach were inferior to those synthesized through colloidal techniques, making it difficult to control the relative positions of electron energy levels in a donor–acceptor system.

Here we demonstrate a colloidal route to the synthesis of PbSe/TiO₂ hetero-nanocrystals (HNCs), comprising 2–5 nm PbSe NCs grown directly on the surface of TiO₂ nanorods (NRs). As a main benefit of colloidal injection techniques, the present approach allows for a controlled adjustment of the sensitizer electronic levels via tuning the average NC diameter during synthesis, which is critical for the experimental realization of a desired type II (staggered) offset of donor and acceptor conduction band edges. Moreover, formation of a near-epitaxial interface between PbSe and TiO₂ domains enables a rapid injection of photoinduced carriers into the oxide material, which was demonstrated via a 50-fold increase in the photoinduced electron-transfer rate between PbSe and TiO₂ domains, as compared to organically linked lead chalcogenide–TiO₂ assemblies.²³

2. Experimental Section

2.1. Chemicals. 1-Octadecene (ODE, 90%, Aldrich), oleylamine (OLAM, 70%, Aldrich), oleic acid (OA, 90%, Aldrich), titanium tetrachloride (TiCl₄, 99.9%, Aldrich), lead(II) oxide powder (PbO, 99.999%, Aldrich), selenium powder (Se, 99.5%, Acros), sulfur (99.999%, Acros), ODE (tech., 90%, Aldrich), tri-n-octylphosphine oxide (TOPO, 99%, Aldrich), selenium (99.5%, Acros), hexane (anhydrous, 95%, Aldrich), methanol (anhydrous, EMD), toluene (anhydrous, 99.8%, Aldrich), and chloroform (anhydrous, 99%, Aldrich) were all used as received without any further purification. All reactions were performed under an argon atmosphere using the standard Schlenk technique.

2.2. Preparation of Injection Precursors. The lead precursor was prepared by dissolving 0.45 g (2.0 mmol) of lead oxide in a mixture of 1.6 g of OA and 4 g of ODE by heating the flask to 200 °C for 30 min. Prior to the injection the temperature of the Pb solution was lowered to 140 °C. One molar TOP-Se solution was prepared by dissolving 0.21 g of Se in 2.7 mL of TOP at room temperature and heated up to 100 °C prior to injection. Two different approaches were used to prepare a sulfur stock solution (see Supporting Information for PbS/TiO₂ het-
The electron beam was accelerated at 20 kV.

X-ray detector located inside a scanning electron microscope.

X-ray (EDX) emission spectra were measured using an EDAX XDS-2000 X-ray powder diffractometer. Energy-dispersive spectrophotometry and a Jobin Yvon Fluorolog FL3-11 fluorescence spectra were recorded using a CARY 50 Scan spectrophotometer and a Jobin Yvon Fluorolog FL3-11 fluorescence spectrophotometer. High-resolution transmission electron microscopy measurements were carried out using a JEOL 3011UHR operated at 300 kV. Specimens were prepared by depositing a drop of nanocrystal hexane solution onto a Formvar-coated copper grid and allowing it dry in air. X-ray powder diffraction measurements were carried out on a Scintag XDS-2000 X-ray powder diffractometer. Energy-dispersive X-ray (EDX) emission spectra were measured using an EDAX X-ray detector located inside a scanning electron microscope. The electron beam was accelerated at 20 kV.

2.5. Fluorescence Lifetime Measurements. FL lifetime measurements were performed using a time-correlated single-photon counting setup utilizing a SPC-630 single-photon counting PCI card (Becker & Hickle CmbH), picosecond diode laser operating at 400 nm, as an excitation source (Picoquant), and an id50 avalanche photodiode (Quantique). The repletion rate of the laser was chosen to allow for a 1000 ns time window, whereas the pulse fluence was adjusted to produce about 1 emission photon per 100 excitation pulses (excitation power was 100 µW).

3. Results and Discussion

In the case of colloidal heterostructures, the type of inorganic interface that forms at the boundary of the two material domains is determined by the relationship between the total surface energy of the composite nanoparticle and the solid—solid interfacial energy related to the mismatch-induced strain between the two lattices. If the interfacial strain exceeds the surface tension of either material, such structure may undergo a spatial rearrangement that eliminates some of the interfacial region by increasing the overall surface area. This scenario is clearly observed for PbSe/TiO2 heterostructures, where a large lattice mismatch of either 6.7% or 18% corresponding to merging of 010 and 110 (Figure 2b) or 001 and 100 facets of anatase TiO2 and rutile PbSe crystal lattices leads to the Volmer—Weber growth of the PbSe material, characterized by the formation of small PbSe islands throughout the surface of TiO2 (Figure 1b).

One potential benefit associated with such a growth mode is the possibility of increasing the optical extinction coefficient of these nanoparticles by sintering several PbSe sensitizers per single TiO2 NR. Since the light-absorption cross section of 2 nm PbSe NCs is generally small (~2 × 10−15 cm2, λ = 400), the maximum number of electron—hole pairs generated in a single PbSe/TiO2 structure, under ambient illumination (photon flux ∼3 × 1017 m−2 s−1) is less than 1, which is not expected to produce nonlinear charging effects. As a result, increasing the number of PbSe sites in PbSe/TiO2 heterostructures should result in a linear increase of the power conversion efficiency in NC-sensitized solar cells.

Another benefit of the Volmer—Weber growth regime is the thermodynamically stable formation of small-diameter PbSe NCs, which is critical for the realization of a type II heterojunction between PbSe and TiO2 materials. Indeed, according to the energy diagram of electronic states in PbSe NCs (Figure 1a), calculated from electron injection studies and empirical scaling of band edge absorption, the transfer of photoinduced electrons from PbSe to TiO2 is energetically permissible only if the size of PbSe is less than 5 nm.

Schematics of the one-pot approach to the synthesis of PbSe/TiO2 HNCs are illustrated in Figure 2a. Growth of TiO2 NRs...
was performed according to a method adapted from ref 32 by heating TiCl₄ to 300 °C in the presence of OA and OLAM. This approach makes use of a high concentration of Ti precursor in the reaction mixture to yield high-aspect ratio anatase nanorods elongated along the (001) crystallographic direction. Upon formation of TiO₂ NRs, the temperature of the reaction mixture was lowered to 180 °C for the growth of PbSe NCs. Typically, a single injection of Pb and Se precursors leads to the formation of 2–3 nm PbSe islands on the surface of nanorods. A small amount of isolated PbSe NCs (<10% of nanoparticles) was also observed in as-prepared reaction mixture and was subsequently reduced to less than 2% after the purification stage (Figure 3a). Additional injections of precursors were needed to fuel the growth of PbSe islands beyond 3 nm in size.

Transmission electron microscopy (TEM) analysis of PbSe/TiO₂ HNCs reveals a qualitative difference between the shapes of PbSe NCs forming on the surface of TiO₂ NRs as a result of single and multiple injections of Pb and Se precursors. The initial injection leads to the formation of several small-diameter PbSe sites per single NR (Figures 2b,c), with an average site diameter of 1.8–3.0 nm and size dispersion of 10–14% (see Figure S1 for the statistical distribution of diameters). We estimate that the number of PbSe NCs per single TiO₂ NR is 21 ± 6, where the dispersion in the number of dots is mainly determined by the dispersion of NR surface areas.

Doubling the concentration of precursors for the first injection was found to produce a 10–15% increase in the density of PbSe dots on the surface of TiO₂, but did not affect an average dot size. According to a high-resolution TEM image of a typical PbSe/TiO₂ HNC in Figure 2c, PbSe dots appear to be uniformly scattered over the entire NR surface and exhibit a moderate dispersion of sizes. A near-symmetric placement of PbSe dots on the surface of TiO₂ can be explained in terms of fundamental energy requirements on the deposition of secondary material in heteroepitaxial growth. Namely, spatially isotropic addition of PbSe monomers onto TiO₂ NRs initially results in the formation of a thin PbSe shell. Subsequent lateral expansion of the shell is associated with the mismatch-induced increase of

![Figure 2.](image1.png)

**Figure 2.** (a) Schematics of the PbSe/TiO₂ synthesis. (b–e) Transmission electron microscopy images of PbSe/TiO₂ HNCs that form after the initial (b,c) and secondary (d,e) injections of Pb and Se precursors.

![Figure 3.](image2.png)

**Figure 3.** (a) Low-magnification transmission electron microscopy (TEM) image of PbSe/TiO₂ HNCs. (b). High-resolution TEM image of the PbSe/TiO₂ interface, showing quasimatching of crystal lattices along the 110 and 010 faces of PbSe and TiO₂, respectively.
PbSe/TiO2 is characteristic of type II heterostructures with non-
PbSe NCs are analyzed in Figure 4. The absorption profile of
also be identified near 700 nm. Its spectral position correlates
corresponding to the band edge absorption in PbSe NCs, can
is approximately equal to that of TiO2, as can be deduced form
NCs. For these structures the volume of the PbSe crystal phase
that the surface of a NR is virtually free of small PbSe sites,
HNC comprising a single 5 nm PbSe NC (Figure 2e) confirms
the interfacial energy, which promotes the collapse of the PbSe
layer into segregated islands.

Secondary injections of precursors were used to induce the
growth of larger PbSe NCs on TiO2 surfaces, (Figure 2d,e). The
amount of PbSe sites per single NR in this case is reduced to
1 (Figure 2e) or 2 (Figure S2a), which indicates that some of
the smaller islands can coalesce into bigger nanoparticles, as
evident in the transitional heterostructure (Figure S2a). Such
transformation is thermodynamically favorable since the com-
bined surface area of PbSe NCs is reduced during aggregation,
causign the reduction in the total surface energy of the
heterostructure. A high-resolution TEM image of a PbSe/TiO2
HNC comprising a single 5 nm PbSe NC (Figure 2e) confirms
that the surface of a NR is virtually free of small PbSe sites,
which supports the coalescence-induced formation of large PbSe
NCs. For these structures the volume of the PbSe crystal phase
is approximately equal to that of TiO2, as can be deduced form
near-equal amplitudes of elemental peaks in EDX spectra
(Figure 4d).

Optical properties of PbSe/TiO2 HNCs incorporating 1.9 nm
PbSe NCs are analyzed in Figure 4. The absorption profile of
PbSe/TiO2 is characteristic of type II heterostructures with non-
zero photon absorption in the spectral range below the band
gap of both PbSe and TiO2 materials. This is expected because
of excitations of intermediate states that exist at the junction of
both materials.35 The highest in energy excitation feature,
corresponding to the band edge absorption in PbSe NCs, can
also be identified near 700 nm. Its spectral position correlates
well35 with an estimation from a TEM average PbSe size of
1.9 nm (Figure S1).

As-prepared PbSe/TiO2 HNCs, comprising small-diameter
PbSe NCs, show a weak emission feature (emission quantum
yield <0.5%) in the 650–900 nm range, as shown in Figure 4a.
Both the position and the width of the FL peak are consistent
with the expected 1S(e)–1S(h) recombination of carriers in 1.9
nm PbSe NCs, implicating the band-edge origin of the emis-
sion.34 Surprisingly, the contribution of trap states into the FL
signal, expected because of a large surface area of PbSe NCs
and the possible formation of electron-trapping defects along
the strained interface of PbSe and TiO2 domains, was not
significant, as evident by the lack of emission originating from
below PbSe band gap.

The dynamics of carrier decay was further investigated using
FL lifetime measurements (Figure 4b). The observed emission
time of 2.1 ns is substantially shorter than expected for
1S(e)–1S(h) excitons in PbSe NCs, for which room-temperature
values in excess of 500 ns were reported.35 We also note that,
for small-diameter PbSe NCs, FL lifetimes are expected to
increase because of the inverse correlation of the radiative rate
and NC band gap.36 In general, there are two main factors that
can potentially lead to such a dramatic decrease of FL lifetimes
in PbSe/TiO2 HNCs: electron trapping at defects and oxidation
of PbSe NCs via carrier transfer to TiO2. As mentioned above,
the signature of trap states emission was not observed in the
FL spectra. Likewise, the FL relaxation trend is not typical of
carrier traps that generally contribute a long-lived component
with decay constants in excess of 1 µs. Therefore, the observed
rapid quenching of FL is attributed to the transfer of photoind-
duced electrons from PbSe NCs to TiO2 NRs. On the basis of
the observed excited-state lifetime, we conclude that the characteris-
tic time scale for photoinduced electron transfer is 2.1 ns, which is significantly faster than 100 ns electron-transfer
times observed for organically linked PbS–TiO2 systems.25

In summary, we report on a solution-phase synthesis of PbSe/
TiO2 heterostructures, comprising small-diameter PbSe nano-
crystals grown on the surface of TiO2 nanorods. Fabricated
materials exhibit an efficient conversion of visible light energy
via a rapid transfer of photoinduced electrons into TiO2 domains.
From the general prospective, the present synthesis demonstrates
an all-inorganic modification of TiO2 surfaces with semiconduc-
tor NCs and could be extended to other nanocrystalline systems,
as shown in the Supporting Information for PbS-sensitized TiO2
NRs. Moreover, the heteroepitaxial growth of lead chalcogenides
is not limited to TiO2 NRs and can be adapted to other
nanostructured forms of TiO2 including porous films and
nanotubes, whereby introducing a colloidal route to sensitization
of TiO2 surfaces without organic-molecular bridging.

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Supporting Information Available: Statistical distributions of
PbSe diameters, synthesis of PbS/TiO2 heterostructures, and
additional TEM images. This material is available free of charge
via the Internet at http://pubs.acs.org.

References and Notes

TiO₂ Nanorods with PbSe Nanocrystals Modification


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