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ISSN 2055-6756



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REVIEW ARTICLE

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NIR light-activated upconversion semiconductor  
photocatalysts



NCNST



Cite this: *Nanoscale Horiz.*, 2019, 4, 10

## NIR light-activated upconversion semiconductor photocatalysts

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Harvesting of near infrared (NIR) light in the abundant and environmentally friendly solar spectrum is particularly significant to enhance the utilization rate of the cleanest energy on earth. Appreciating the unique nonlinear optical properties of upconversion materials for converting low-energy incident light into high-energy radiation, they become the most promising candidates for fabricating NIR light-active photocatalytic systems by integrating with semiconductors. The present review summarizes recent NIR light-active photocatalytic systems based on a sequence of NaYF<sub>4</sub>-based, fluoride-based, oxide-based and Ln<sup>3+</sup> ion-doped semiconductor-based photocatalysts for degradation of organic molecules. In addition, we provide an in-depth analysis of various photocatalytic mechanisms and enhancement effects for efficient photo-redox performance of different upconversion semiconductor photocatalysts. We envision that this review can inspire multidisciplinary research interest in rational design and fabrication of efficient full-spectrum active (UV-visible-NIR) photocatalytic systems and their wider applications in solar energy conversion.

Received 2nd July 2018,  
Accepted 13th August 2018

DOI: 10.1039/c8nh00154e

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## 1. Introduction

Currently, steadily worsening environmental pollution is an overwhelming global crisis that threatens the health of human beings and sustainable development of natural ecosystems. To solve these urgent issues, the exploitation of green and

environmentally friendly technologies for alternative energy conversion and environmental remediation is proven to be an imperative requirement.<sup>1</sup> Among the various approaches, photocatalysis is valuable for environmental protection and remediation of contaminants as it can efficiently utilize the solar spectrum or artificial light sources, and thus lead to virtually unlimited energy source all over the world.<sup>2–5</sup> Especially, semiconductor-based photocatalysts such as TiO<sub>2</sub>, ZnO, SnO<sub>2</sub>, etc., have been widely applied in photodegradation and photo-oxidization of hazardous organic molecules.<sup>6–9</sup> The initial explanation of n-type TiO<sub>2</sub> electrode in 1972 by Fujishima and Honda (Honda–Fujishima effect) was a significant milestone for semiconductor photocatalysis.<sup>10</sup> And the first description

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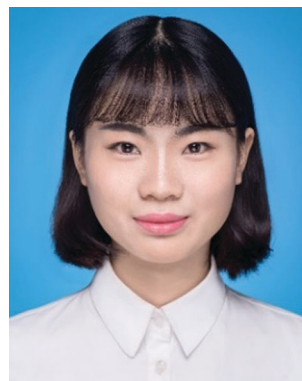
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of  $\text{TiO}_2$  suspension for the photodegradation of polychlorinated biphenyl and cyanide by Cary and Bard in 1980 opened a new gate for  $\text{TiO}_2$ -based semiconductors for the elimination of environmental pollution.<sup>11,12</sup>  $\text{TiO}_2$  possesses the advantages of cost-effectiveness and pollution-free and sustainable development and has been widely investigated in recent decades. However, the wide bandgap of  $\text{TiO}_2$  ( $> 3.0$  eV) has been a major limitation for efficient utilization of solar photons.<sup>13–15</sup> The light absorption threshold is confined in the ultraviolet (UV) region (300–400 nm), which only accounts for 5% of the full spectrum. Therefore, the losses in solar conversion efficiency have resulted in under-utilization of visible (43%, 400–700 nm) and NIR light (52%, 700–2500 nm). Narrow bandgap semiconductors, such as CdS,  $\text{Fe}_2\text{O}_3$ ,  $\text{g-C}_3\text{N}_4$ , etc., could broaden the absorption threshold to the visible region and demonstrate efficient photocatalytic performance.<sup>16,17</sup> NIR-light-active semiconductors with narrower bandgap could further absorb NIR light, while the lower-lying conduction band (CB) and higher-lying valence band (VB) present fairly inert photodecomposition or photo-oxidization abilities to organic dyes. Carbon quantum dots (CQDs) with both up- and down-converted photoluminescence (PL) and photoinduced electron transfer ability could give rise to intense absorption of NIR light.<sup>18,19</sup> The surface plasmon resonance (SPR) peaks of noble-metal plasmonic nanoparticles can be red-shifted to the NIR region by rational adjustment of sizes, morphologies and alloying compositions.<sup>20,21</sup> Their tunable optical characteristics make CQDs and noble-metal plasmonic nanoparticles alternative co-catalysts to harvest NIR photons and enhance the NIR-induced photocatalytic performance. However, the inherent photocorrosion susceptibility and high processing cost make them far from practical propositions. Therefore, much effort should be made to introduce NIR light into semiconductor-based photocatalyst systems.<sup>22,23</sup>

One increasingly appealing and practical approach is coupling photocatalytic semiconductors with nonlinear optical materials that could utilize the abundant NIR light in photocatalysis, to improve the utilization of solar energy, and finally enhance the photoreactions.<sup>24,25</sup> Of especial note are the anti-Stokes luminescence mechanism-based upconversion materials, with the unique property to sequentially absorb two or multiple low-energy photons and radiate out specific types of photons with shorter wavelength, which are considered as potentially efficient candidates for exploitation of NIR excitation. Lanthanide ion ( $\text{Ln}^{3+}$ )-doped upconversion materials with abundant f-orbital configurations have narrow fluorescence emission bands *via* intra-4f ( $4f^n-4f^n$ ) or 4f-5d ( $4f^n-4f^{n-1}5d$ ) orbital transitions.<sup>26,27</sup> The involved symmetries of inner electronic quantum states would yield metastable energy levels with long lifetimes that favor the incidence of successive populations in the energized states of  $\text{Ln}^{3+}$  ions. Under NIR laser irradiation, the pump photons in the ground state of sensitizer ions will be sequentially excited to the excited states of activator ions. Then, the population will relax non-radiatively or radiatively to the ground state of activator ions to achieve the upconversion emissions. The perfect shielding effect of outer 5s and 5p shells of  $\text{Ln}^{3+}$  prevents the influence of surrounding environment on electronic transitions, resulting in perfect physical and chemical stability against photobleaching and photochemical degradation. Doping with different  $\text{Ln}^{3+}$  ions in an inorganic substrate will induce designable upconversion emissions, from the UV, passing through the entire visible and extending to the NIR region under irradiation.<sup>28–30</sup> Fig. 1 presents the occupation of  $\text{Ln}^{3+}$  ion-doped upconversion materials with large absorption cross section for converting the NIR light in the solar spectrum into visible light. The main adsorption centers of the  $\text{Ln}^{3+}$  ions, *i.e.*,  $\text{Nd}^{3+}$ ,  $\text{Yb}^{3+}$ ,  $\text{Ho}^{3+}$  and  $\text{Er}^{3+}$ , are located at 808 ( $\text{Nd}^{3+}$ :  $^4\text{I}_{9/2}-^4\text{F}_{5/2}$ ), 980 ( $\text{Yb}^{3+}$ :  $^2\text{F}_{7/2}-^2\text{F}_{5/2}$ ), 1160 ( $\text{Ho}^{3+}$ :  $^5\text{I}_8-^5\text{I}_6$ )



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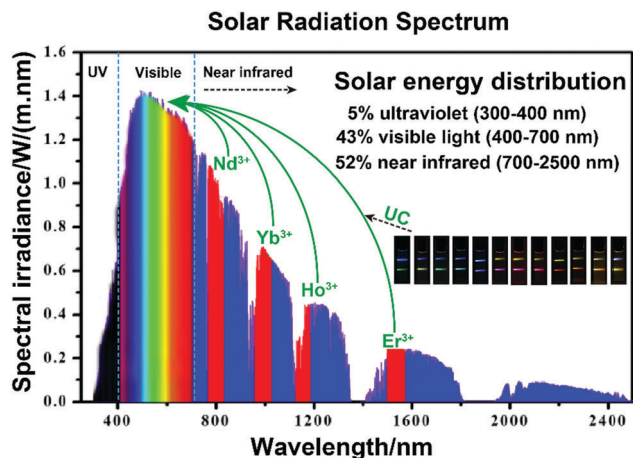


Fig. 1 The schematic conversion processing of NIR light into visible light via  $\text{Ln}^{3+}$  ions, referring to standard AM 1.5 solar radiation spectrum, and the tunable emissions of upconversion materials.

and 1530 ( $\text{Er}^{3+}: {}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{13/2}$ ) nm, respectively.<sup>31</sup> These ions will act as sensitizers that absorb the centered NIR photons and emit UV or visible photons through multiple photon absorption or energy transfer processes. For instance, tunable emissions varying from blue to red colors can be realized by fine-tuning the concentration of sensitizer  $\text{Yb}^{3+}$  ions and changing the doped activator  $\text{Tm}^{3+}$  and  $\text{Er}^{3+}$  ions.<sup>32</sup> The spectral power from the normalized air mass (AM) 1.5 spectrum yield is nearly

$25 \text{ W m}^{-2}$  ranging from 1480 to 1580 nm when  $\text{Er}^{3+}$  acts as the activator.<sup>33</sup> It will be extremely attractive to combine upconversion materials as frequency conversion elements with UV- or visible-active semiconductor photocatalysts to further harvest solar energy in a broader spectral range, and thus promoting the utilization of solar energy efficiently.

## 2. The $\text{Ln}^{3+}$ ion-doped upconversion mechanism

The upconversion emissions are based on the transition of 4f electronic configurations between rare earth (RE) ions (Sc, Y and La are technically d-shell elements).<sup>34</sup> Each kind of RE ion has its definite energy level positions, and the upconversion processes between different RE ions are different from each other, while all of them represent similar property of chemical elements attributed to the dominant trivalent oxidation state. The characteristic energy level positions of different  $\text{Ln}^{3+}$  ions are illustrated in Fig. 2, which was well defined by experimental measurement by Dieke (Dieke diagram) and Carnall *et al.*<sup>31,35</sup> The energy level positions give detailed illustration of absorption and excitation spectra of  $\text{Ln}^{3+}$  ion-doped upconversion materials with distinguishable spectroscopic fingerprints. The upconversion process has been recognized to be grouped into three stages: excited state absorption (ESA), energy transfer (ET), and phonon avalanche (PA).

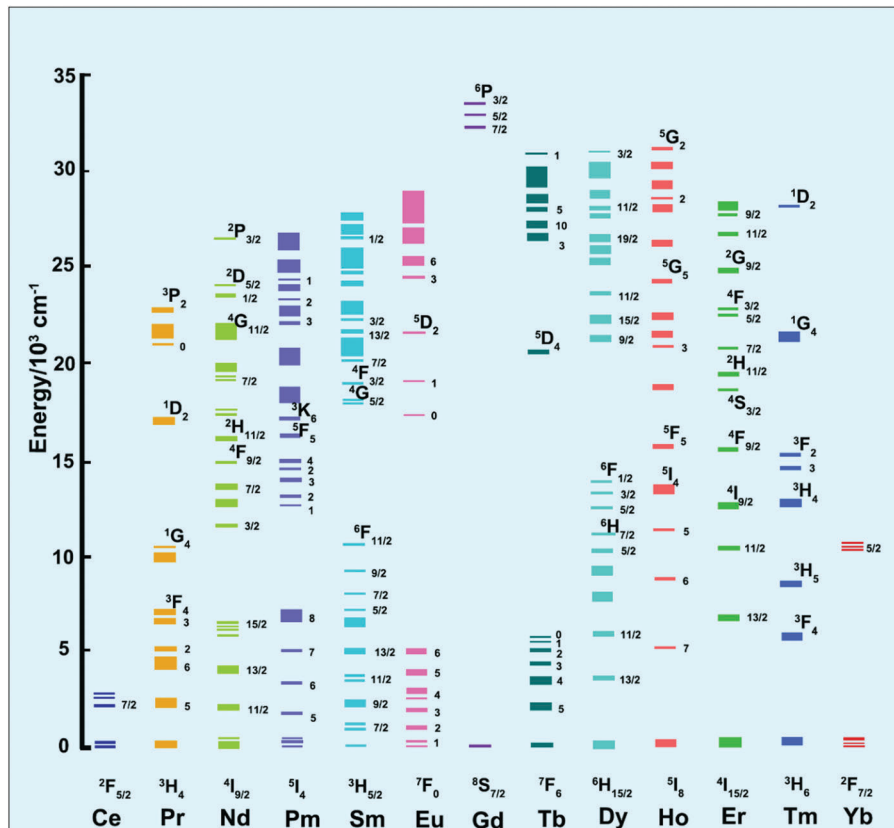


Fig. 2 Characteristic energy level positions of a sequence of  $\text{Ln}^{3+}$  ions.

## 2.1 Excited state absorption (ESA)

ESA is the basic process of upconversion luminescence first proposed by Bloembergen *et al.* in 1959.<sup>36</sup> The mechanism is that one type of  $\text{Ln}^{3+}$  ion is excited from the ground state (GS) to an excited state with high energy level through sequential two- or multiphoton absorption. Typically, as illustrated in Fig. 3a, the  $\text{Ln}^{3+}$  ion absorbed one photon  $h\nu_1$  and is promoted from GS to intermediate metastable (electronic) state ( $E_1$ ). Because of the long relaxation time of metastable energy level, the excited ions will stay or decay between the intra-band for a long time. And then, if another energy-matched photon matches the energy interval between  $E_1$  and upper excited state  $E_2$ , the ions at state  $E_1$  will absorb the photon energy and populate the state  $E_2$ , achieving successive absorption of two photons. Three or more multiphoton absorption processes will be deduced by analogy. Finally, the excited ions relax non-radiatively or radiatively to the GS, inducing the upconversion emissions. Additionally, supposing the incident photons are sequentially trapped by individual  $\text{Ln}^{3+}$  ions, then the upconversion efficiency of the ESA process is independent of the  $\text{Ln}^{3+}$  doping concentration. The usual doping concentration of  $\text{Ln}^{3+}$  ions is less than 1%.<sup>37</sup> Under continuous excitation, the intensity of upconversion luminescence ( $I_{\text{uc}}$ ) is proportional to excitation power ( $I_{\text{ex}}$ ):

$$I_{\text{em}} \propto (I_{\text{ex}})^n \quad (1)$$

where  $n$  is the number of pump photons.

## 2.2 Energy transfer upconversion (ETU)

The ETU process generally occurs between two types of ions (donor and acceptor) in close proximity *via* dipole-dipole interaction. High concentration of dopants is required in ETU process-dominated upconversion materials, as the dopant content determines the distance between the proximal ions. ETU can be classified into three categories based on diverse

energy transfer types: successive energy transfer (SET), cross relaxation (CR) and cooperative upconversion (CU).

**2.2.1 Successive energy transfer (SET).** The SET process is illustrated in Fig. 3b. The donor ions in the excited state should match the energy requirement with proximal acceptor ions in the ground state. Consequently, the donor ions will transfer energy to the acceptor ions and excite them into the excited state ( $E_1$ ), albeit themselves will return to the GS through non-radiative relaxation. The excited acceptor ions may be promoted to higher excited state ( $E_2$ ) *via* successive energy transfer.

**2.2.2 Cross relaxation (CR).** The CR process between one or two types of neighboring ions is displayed in Fig. 3c. Both  $\text{Ion}_1$  and  $\text{Ion}_2$  ( $\text{Ion}_1$ ) are populating the intermediate energy level ( $E_1$  and  $E_2$ ). Then,  $\text{Ion}_2$  ( $\text{Ion}_1$ ) would be motivated to higher intermediate energy level ( $E_3$ ) in accordance with the non-radiatively energy transfer processes of proximal  $\text{Ion}_1$ , accompanied by the relaxation of  $\text{Ion}_1$  to the ground state.

**2.2.3 Cooperative upconversion (CU).** Three ions are involved in the CU process (Fig. 3d), where the two excited ions ( $\text{Ion}_1$  and  $\text{Ion}_2$ ) transfer the energy to the third ion ( $\text{Ion}_3$ ) simultaneously and emit  $\text{Ion}_3$  from the GS to higher energy level, while  $\text{Ion}_1$  and  $\text{Ion}_2$  relax non-radiatively to the GS. The CU process involves the interaction between three ions, and the acceptor ions require a matched metastable energy level with donor ions; therefore, the CU process always occurs with low probability.<sup>31</sup>

## 2.3 Phonon avalanche (PA)

The PA process was proposed firstly from an investigation of the upconversion spectrum of  $\text{Pr}^{3+}$ -doped lanthanum chloride ( $\text{LaCl}_3$ ) host by Chivian.<sup>38</sup> The PA process is an unconventional looping process of ESA and CR, which contains four procedures of energy transfer (Fig. 3e). (I) The  $\text{Ion}_2$  initially emerges to the intermediate level ( $E_1$ ) by GS energy transition. (II) This is followed by energy transfer by ESA or ETU process to populate the higher excited energy level ( $E_2$ ) where the upconversion luminescence occurred. And then (III) a CR process occurred among activated  $\text{Ion}_2$  and proximal ground-state  $\text{Ion}_1$ , causing two populations in the metastable state  $E_1$ . (IV) Finally, the looping process readily populates and exponentially increases the population of excited state  $E_2$  through ESA process, invoking intense upconversion radiation like an avalanche process. The PA process is highly dependent on the pump intensity, which should be higher than the threshold value of metastable energy level.<sup>39</sup>

In addition, with the rapid development of core-shell nanostructured upconversion materials, a new energy migration-mediated upconversion (EMU) mechanism was proposed recently (Fig. 3f).<sup>40,41</sup> This involves successive energy transfer from the sensitizers (S) to accumulators (A') and migrators (M), and trapped by activators (A), finally inducing the upconversion process.

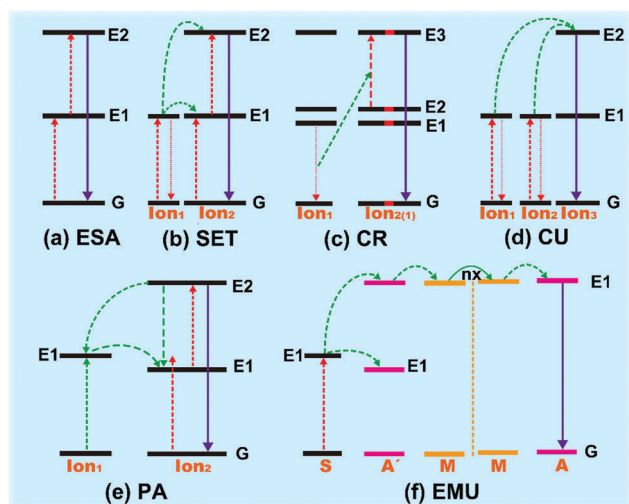


Fig. 3 Principal diagram for the upconversion processes of  $\text{Ln}^{3+}$ -doped crystals. (a) ESA, (b) SET, (c) CR, (d) CU, (e) PA and (f) EMU. The red, green, and purple lines stand for photon excitation, energy transfer, and emission processes, respectively.

## 3. The $\text{Ln}^{3+}$ ion-doped upconversion materials

The upconversion efficiency of  $\text{Ln}^{3+}$  ion-doped materials is reliant on the crystal structures, local site symmetry, crystal

field strength, and phonon energy of the host matrixes. It will be a key factor to choose appropriate host matrixes to achieve favorable optical performance of upconversion materials with high upconversion luminescence efficiency. Currently, the majority of upconversion materials are doped with  $\text{Ln}^{3+}$  ions into appropriate dielectric host matrix. The doped  $\text{Ln}^{3+}$  ions are randomly distributed in the cation sites, which are offered by the ordered array of host matrixes.<sup>42</sup> The host matrixes generally do not constitute the exciting energy levels but will provide suitable crystal field for the doped  $\text{Ln}^{3+}$  ions that enables corresponding emissions. Host matrixes with low phonon energy are preferred for effective upconversion luminescence, because multi-phonon supported non-radiative relaxations between the nearest spaced energy levels can be minimized, thus greatly prolonging the lifetime of intermediate levels. The non-radiative relaxation probability ( $W_p$ ) induced by multi-phonon relaxation is expressed as:<sup>43,44</sup>

$$W_p = C \left[ \frac{\exp(h\nu/KT)}{\exp(h\nu/KT)-1} \right]^P e^{-\alpha\Delta E} \quad (2)$$

where  $P$  is the order of phonons ( $P = \Delta E/h\nu$ ),  $\Delta E$  is the gap between two energy levels,  $\nu$  is the phonon frequency,  $h$  is the Boltzmann constant, and  $\alpha$  and  $C$  are constants related to matrix materials.  $P$  will increase with decreasing phonon energy, resulting in the decrease of non-radiative relaxation possibility, thus enhancing the upconversion luminescence efficiency. Furthermore, the increased lifetime of metastable energy levels will prohibit the quenching of radiative transitions in the upconversion process. The phonon energy depends on the crystal lattice of host matrixes, and charge and diameter of anions implanted in the crystal. When the phonon energy matches the frequency of excitation or emission, the absorption of the crystal lattice can reduce the emission efficiency, and thus the host matrix is desirable to occupy with lower phonon energy. The most investigated host matrixes include low phonon energy (fluorides  $\sim 355 \text{ cm}^{-1}$ , chlorides  $\sim 260 \text{ cm}^{-1}$ , oxides  $\sim 600 \text{ cm}^{-1}$ , iodides  $\sim 144 \text{ cm}^{-1}$ , bromides  $\sim 172 \text{ cm}^{-1}$ , etc.) and high phonon energy (silicates  $\sim 1000 \text{ cm}^{-1}$ , borates  $\sim 1100 \text{ cm}^{-1}$ , phosphates, etc.) materials,<sup>35,45–47</sup> as listed in Table 1. Considering the effect of the photon energy of host matrixes on the upconversion luminescence, the efficiency increases in the order of oxides < fluorides < chlorides < bromides < iodides. Comparatively, heavy halides are hygroscopic, and the structural stability of the matrixes decreased in inversed proportional of oxides > fluorides > chlorides. Therefore, a series of investigations were carried out, expecting to find new-fashioned host matrixes with advantages of high upconversion efficiency (like fluorides and chlorides) and high stability (like oxides), to achieve practical applications. Typically, the hexagonal  $\text{NaYF}_4$  crystal with low phonon energy and excellent chemical stability is accepted to be the most efficient host material hitherto.

In the following section, the effectiveness of commonly investigated upconversion materials with different host matrixes that are applied in the field of photocatalysis, including a sequence of  $\text{NaYF}_4$ -based, fluoride-based, oxide-based and

Table 1 The phonon energy of various host matrixes

| Host matrix | Phonon energy ( $\text{cm}^{-1}$ ) | Host matrix | Phonon energy ( $\text{cm}^{-1}$ ) |
|-------------|------------------------------------|-------------|------------------------------------|
| Fluorides   | $\sim 355$                         | Silicates   | $\sim 1000$                        |
| Chlorides   | $\sim 260$                         | Borates     | $\sim 1100$                        |
| Iodides     | $\sim 144$                         | Phosphates  | $\sim 1300$                        |
| Bromides    | $\sim 172$                         | Bismuthates | $\sim 1192$                        |
| Oxides      | $\sim 600$                         |             |                                    |

$\text{Ln}^{3+}$  ion-doped semiconductor-based photocatalysts, is discussed in detail.

## 4. The upconversion semiconductor-based photocatalysts

### 4.1 The mechanism of upconversion semiconductor-based photocatalysts

The proposed photocatalytic mechanism of semiconductor-based upconversion photocatalysts is illustrated in Fig. 4. The upconversion materials serve as the frequency conversion element and harvest two or multiple NIR light photons and then convert them into UV or visible light photons *via* an efficient fluorescent resonance energy transfer (FRET) process. Subsequently, the converted photons can be re-absorbed by the surrounding semiconductors and inject the electrons from VB to CB of semiconductors, thereby increasing the yield of photoinduced carriers. The direct energy migration between the combination of UC materials and semiconductors under NIR light irradiation could extend the utilization of the solar spectrum and promote the photocatalytic efficiency.

### 4.2 The $\text{NaYF}_4$ -based upconversion photocatalysts

RE ion-doped sodium fluoride matrix contains two different types of crystal phases, including cubic and hexagonal phases (Fig. 5a and b). In the cubic phase, the host  $\text{F}^-$  ions form a high-symmetry cubic crystal structure, with  $\text{Na}^+$  and  $\text{RE}^{3+}$  ions randomly occupying the cation sites. Comparatively, the  $\text{Na}^+$  and  $\text{RE}^{3+}$  ions are selectively occupying the two types of relatively low-symmetry cation sites that are contained in regular crystal sublattices of  $\text{F}^-$  ions in hexagonal  $\text{NaYF}_4$ .<sup>42</sup>

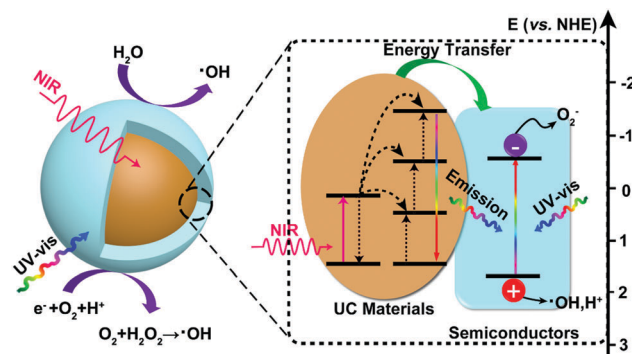


Fig. 4 The proposed photocatalytic enhancement mechanism for semiconductor-based upconversion photocatalysts.



Generally, host crystal lattices with low site symmetry of doping lanthanoids are preferable for upconversion luminescence over their higher symmetry counterparts, because low-symmetry lattices ordinarily have a crystal field with lots of uneven components surrounding the doping ions. The uneven components strengthen the electronic coupling among 4f electronic orbits and their higher electronic configuration and subsequently promote 4f–4f transition possibilities of the doping ions.<sup>48</sup> The density functional theory (DFT)-calculated charge densities for cubic and hexagonal NaREF<sub>4</sub> crystals are presented in Fig. 5c and d. In the hexagonal phase, the Ln<sup>3+</sup> dopants increase the asymmetry distribution and improve the charge transfer, resulting in an enhancement of polarizability and formation energy. Therefore, hexagonal phase NaREF<sub>4</sub> nanocrystals exhibited an order of magnitude augmentation in upconversion efficiency when compared with cubic phase.<sup>49</sup> Especially, the hexagonal phase NaYF<sub>4</sub>, having the advantages of wide energy bandgap ( $\sim 8$  eV)<sup>50</sup> and a very low phonon energy ( $\sim 360$  cm<sup>-1</sup>  $\approx$  45 meV),<sup>51,52</sup> has been considered as one of the most efficient upconversion host matrixes for decades. And most photocatalysts have been combined with hexagonal phase NaYF<sub>4</sub> to achieve efficient NIR-active photocatalytic systems.

The photodegradation performance of NaYF<sub>4</sub>-based semiconductor photocatalysts is presented in Table 2. As mentioned above, TiO<sub>2</sub> attracts extensive interest as a photocatalyst because the numerous advantages like abundance, chemical stability, environmental friendliness, and high photocatalytic activities. Incorporating upconversion materials with TiO<sub>2</sub> will extend the absorption edge up to the NIR region and finally achieve higher photocatalytic efficiency.<sup>53–57</sup> For example, core-shell NaYF<sub>4</sub>:Yb,Tm@TiO<sub>2</sub> nanoparticles show excellent activities under both UV and NIR irradiation for photodegradation of RhB dyes.<sup>55</sup> And the photocatalytic activities of NaYF<sub>4</sub>:Yb,Tm@TiO<sub>2</sub> nanoparticles vary with the sizes of the

NaYF<sub>4</sub> core (Fig. 6a–d), the optimum core size being about 50 nm, which is beneficial to the photocatalytic performance of the TiO<sub>2</sub> shell. In addition, the size-dependent upconversion mechanism of NaYF<sub>4</sub>:Yb<sup>3+</sup>,Er<sup>3+</sup> nanoparticles has been experimentally and theoretically demonstrated, confirming the competition process between the upconversion population and non-radiative relaxation.<sup>58</sup> Another group further synthesized shell thickness-controllable NaYF<sub>4</sub>@TiO<sub>2</sub> core-shell composites by varying the ratio of Yb<sup>3+</sup>,Tm<sup>3+</sup> co-doped NaYF<sub>4</sub> micro-rods and Ti precursors (Fig. 6e–h), proving that optimum shell thickness is beneficial to the photocatalytic performance.<sup>57</sup> As displayed in Fig. 6i, when a thin TiO<sub>2</sub> shell is coated, only a small part of the UV radiation would be captured by the TiO<sub>2</sub> layer and most of it will be scattered and wasted. On the contrary, a thick TiO<sub>2</sub> shell will greatly inhibit the upconverted emissions penetrating to the external surface and largely increase the recombination possibilities of photogenerated carriers, which is also detrimental to photocatalytic performance. Furthermore, other upconversion material–semiconductor composite photocatalytic systems are rationally designed. For example, NaYF<sub>4</sub>:Yb/Tm–BiOCl,<sup>59</sup> NaYF<sub>4</sub>:Yb/Er–MoS<sub>2</sub>,<sup>60</sup> NaYF<sub>4</sub>:Yb/Tm–g-C<sub>3</sub>N<sub>4</sub>,<sup>61,62</sup> NaYF<sub>4</sub>:Yb/Tm–CdS,<sup>63,64</sup> NaYF<sub>4</sub>:Yb/Er–CdSe,<sup>65</sup> NaYF<sub>4</sub>:Yb/Tm–ZnO,<sup>66,67</sup> and NaYF<sub>4</sub>:Yb/Tm–MOFs<sup>68</sup> have been designed and constructed as NIR-responsive photocatalysts. Ternary heterogeneous materials are also developed and applied as highly efficient UV-visible-NIR full-spectra active photocatalysts.<sup>69,70</sup>

Unfortunately, upconversion nanomaterials always suffer the drawbacks of low quantum yields and intense luminescence quenching, mainly resulting from the comparatively insensitive extinction coefficients of lanthanide dopants.<sup>27</sup> Innovative methods have been investigated for enhancing the upconversion intensity in lanthanide-doped nanocrystals, including surface plasmon coupling, surface passivation, energy transfer modulation, *etc.*<sup>27</sup> Especially, the surface plasmon coupling of noble metals with upconversion material–semiconductor system presents fascinating NIR-driven photocatalytic performance.<sup>71–74</sup> Surface plasmon coupling of noble metals with upconversion materials improves the upconversion luminescence from three aspects as follows: (1) enhancing the absorption of the sensitizer through electric-field coupling, (2) improving the radiative decay rate of the activator, and (3) increasing energy transfer from the sensitizer to the activator, as displayed in Fig. 7a. The SPR-induced local electric field could enhance the photon flux and affect the radiative decay rates of the activators, thereby leading to enhanced upconversion luminescence and high quantum yield.<sup>75,76</sup> In our previous work, finite-difference time-domain analysis (FDTD) was used to stimulate the electromagnetic field intensity of upconversion and plasmonic enhanced photocatalysts under each of UV, visible and NIR light irradiation (Fig. 7b–e). The SPR effect of Ag nanoparticles leads to higher photocarrier yield and improves the efficient transfer of photocarriers and energy, resulting in quintupled enhancement of photocatalytic efficiency.<sup>72</sup> The plasmon and upconversion enhanced broadband photocatalysts NYF@TiO<sub>2</sub>–Au are synthesized with significantly superior photocatalytic performance to the commercial P25 TiO<sub>2</sub>.<sup>71</sup> Fig. 7f illustrates the NIR-active photocatalytic mechanism.

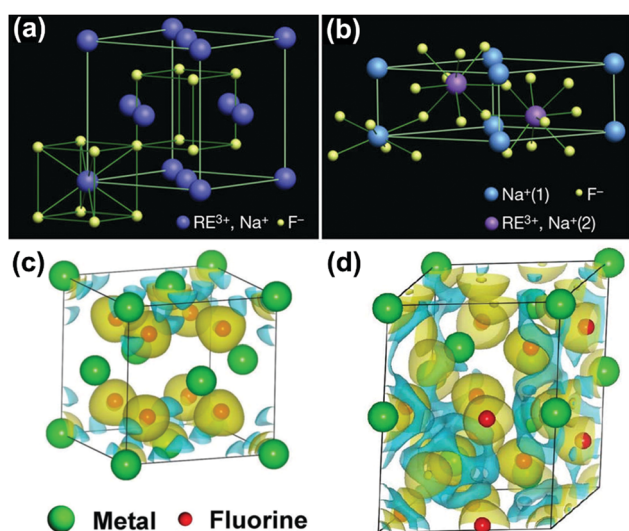


Fig. 5 (a) Cubic and (b) hexagonal type crystal phases of Ln<sup>3+</sup>-doped NaYF<sub>4</sub> and DFT-calculated charge density for (c) cubic and (d) hexagonal NaYF<sub>4</sub>. (Reproduced with permission.<sup>42</sup> Copyright 2010, Springer Nature.)

Table 2 Photodegradation performance of NaYF<sub>4</sub>-based semiconductor photocatalysts

| Photocatalyst (mg)                                                                            | Light source                           | Pollutant <sup>a</sup> (concentration, mg L <sup>-1</sup> /volume, mL) | Degradation ratio/time (h) | Ref. |
|-----------------------------------------------------------------------------------------------|----------------------------------------|------------------------------------------------------------------------|----------------------------|------|
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub> (0.5)                                               | 980 nm laser (10 W cm <sup>-2</sup> )  | MB (15/0.5)                                                            | 65%/14                     | 53   |
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub> (20)                                                | 980 nm laser (0.5 A)                   | RhB (10 <sup>-5</sup> M/10)                                            | 22%/1 (83%/6)              | 54   |
|                                                                                               | ARC lamp (69920)                       | Phenol (10 <sup>-5</sup> M/50)                                         | 17%/1 (53%/6)              |      |
| NaYF <sub>4</sub> :Yb,Tm@TiO <sub>2</sub> (7)                                                 | 50 W Xe lamp                           | RhB (5 × 10 <sup>-5</sup> M/50)                                        | 100%/0.5                   | 55   |
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub>                                                     | 1 W 980 nm laser                       | MB (20/0.5)                                                            | 68%/24                     | 56   |
|                                                                                               |                                        | MO (15/0.5)                                                            | 69%/24                     |      |
|                                                                                               |                                        | RhB (10/0.5)                                                           | 76%/76                     |      |
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub> (10)                                                | 1.5 W 980 nm laser                     | MB (5/1)                                                               | 90%/12                     | 57   |
| NaYF <sub>4</sub> :Yb/Tm-BiOCl (20)                                                           | 300 W Xe lamp, λ > 780 nm              | RhB (10/50)                                                            | 100%/2.7                   | 59   |
|                                                                                               |                                        | MB (10/50)                                                             | 58%/2.7                    |      |
| MoS <sub>2</sub> -NaYF <sub>4</sub> :Yb/Er (20)                                               | 980 nm laser                           | RhB (25/10)                                                            | 61%/12                     | 60   |
| NaYF <sub>4</sub> :Yb/Tm/g-C <sub>3</sub> N <sub>4</sub> (1)                                  | 1 W 980 nm laser                       | MB (15/0.5)                                                            | 83%/6                      | 61   |
|                                                                                               | 300 W Xe lamp                          |                                                                        | 89%/1.5                    |      |
| NaYF <sub>4</sub> :Yb/Tm/g-C <sub>3</sub> N <sub>4</sub> (10)                                 | 1 W 980 nm laser                       | RhB (10/100)                                                           | 22%/7                      | 62   |
|                                                                                               | 50 W Xe lamp                           |                                                                        | 80%/1.75                   |      |
| NaYF <sub>4</sub> :Yb/Tm-CdS (20)                                                             | 2 W 976 nm laser                       | RhB (10/10)                                                            | 13%/3                      | 63   |
| (40)                                                                                          | 300 W Tu lamp                          | (50/20)                                                                | 72%/2.5                    |      |
| NaYF <sub>4</sub> :Yb/Tm@C@CdS (10)                                                           | 50 W Xe lamp                           | RhB (10 <sup>-5</sup> M/50)                                            | 92%/1.2                    | 64   |
|                                                                                               |                                        | MB (10 <sup>-5</sup> M/50)                                             | 95%/1.2                    |      |
| NaYF <sub>4</sub> :Yb/Er-CdSe (0.5)                                                           | 2 W 1560 nm laser                      | MB (15/0.5)                                                            | 65%/30                     | 65   |
|                                                                                               | 2 W 980 nm laser                       |                                                                        | 75%/30                     |      |
| NaYF <sub>4</sub> :Yb/Tm-ZnO (0.5)                                                            | 2 W 980 nm laser                       | RhB (20/0.5)                                                           | 65%/30                     | 66   |
| NaYF <sub>4</sub> :Yb/Tm@SiO <sub>2</sub> -ZnO (50)                                           | 980 nm laser (50 mW cm <sup>-2</sup> ) | RhB (10/50)                                                            | 17%/7                      | 67   |
|                                                                                               | 50 W Xe lamp                           |                                                                        | 89%/1.7                    |      |
| NaYF <sub>4</sub> :Yb/Tm/MOFs (20)                                                            | Xe lamp (100 mW cm <sup>-2</sup> )     | RhB (10/50)                                                            | 85%/1.5                    | 68   |
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub> /RGO (5)                                            | 2 W 980 nm laser                       | MB (10/5)                                                              | 81.1%/12 (90%/1)           | 69   |
|                                                                                               | 300 W Xe lamp                          | MO (15/5)                                                              | 45.9%/12 (90%/1)           |      |
|                                                                                               |                                        | Phenol (20/5)                                                          | 29.8%/12 (61%/1)           |      |
| NaYF <sub>4</sub> :Yb/Er@TiO <sub>2</sub> -Ag <sub>6</sub> Si <sub>2</sub> O <sub>7</sub> (5) | 2 W 980 nm laser                       | MB (10/10)                                                             | 45%/5                      | 70   |
|                                                                                               | 300 W Xe lamp                          |                                                                        | 100%/2 min                 |      |
| NaYF <sub>4</sub> @TiO <sub>2</sub> -Au (10)                                                  | 8 W UV lamps                           | MO (20/100)                                                            | 95%/1                      | 71   |
|                                                                                               | 300 W Xe lamp (λ > 420 nm)             |                                                                        | 83%/8                      |      |
|                                                                                               | 2 W 980 nm laser                       |                                                                        | 80%/20                     |      |
|                                                                                               | 150 W solar simulator                  |                                                                        | 80%/2                      |      |
| NaYF <sub>4</sub> :Yb/Tm@SnO <sub>2</sub> /Ag (5)                                             | 2 W 980 nm laser                       | RhB (10/10)                                                            | 100%/5                     | 72   |
|                                                                                               | 300 W Xe lamp                          |                                                                        | 100%/0.17                  |      |
| NaYF <sub>4</sub> :Yb/Tm@TiO <sub>2</sub> /Ag                                                 | 50 W Xe lamp                           | R6G (10 <sup>-5</sup> M/50)                                            | 96%/2                      | 73   |
| NaGdF <sub>4</sub> :Yb/Er-mTiO <sub>2</sub>                                                   | AM 1.5 solar light                     | RhB                                                                    | 99%/0.8                    | 77   |
| NaGdF <sub>4</sub> :Er/Yb@BiFeO <sub>3</sub> (20)                                             | 980 nm laser (80 mW mm <sup>-2</sup> ) | MO (10/20)                                                             | 55%/3.5                    | 78   |
|                                                                                               | 500 W Xe lamp (λ > 420 nm)             |                                                                        | 80%/15                     |      |
| NaLuF <sub>4</sub> :Gd,Yb,Tm@SiO <sub>2</sub> @TiO <sub>2</sub> :Mo                           | 500 W Xe lamp                          | RhB (20/50)                                                            | 100%/3.5                   | 79   |
|                                                                                               | 980 nm laser                           |                                                                        | 90%/3.5                    |      |
| NaGdF <sub>4</sub> :Yb:Er/Ag/TiO <sub>2</sub> (8)                                             | 1.5 W 980 nm laser                     | RhB (5/5)                                                              | 40%/18                     | 80   |
| (40)                                                                                          | 500 W UV-vis light                     | (40/40)                                                                | 97%/0.5                    |      |
| NaYF <sub>4</sub> :Yb/Tm@NaYF <sub>4</sub> /TiO <sub>2</sub> (10)                             | 8 W 980 nm laser                       | RhB (1.43/5)                                                           | 41%/6                      | 85   |
|                                                                                               | 250 W Xe lamp                          |                                                                        | 73%/0.42                   |      |
| NaYF <sub>4</sub> :Tm/Yb@Yb/Nd@N-TiO <sub>2</sub>                                             | Xe lamp (100 mW cm <sup>-2</sup> )     | RhB (10 <sup>-5</sup> M/50)                                            | 96%/1.5                    | 86   |

<sup>a</sup> MB represents methylene blue; RhB represents Rhodamine B; MO represents methyl orange; R6G represents Rhodamine 6G.

Under NIR light irradiation, Er<sup>3+</sup> and Tm<sup>3+</sup> co-doped NaYF<sub>4</sub> excites UV and visible emissions, which overlap with the intrinsic light absorption of TiO<sub>2</sub> and SPR band of Au nanoparticles. The excited UV emissions will assist the TiO<sub>2</sub> to generate reductive electrons and highly oxidative holes. The excited visible emissions will interact with the SPR effect of Au nanoparticles to facilitate the transfer of hot electrons to nearby TiO<sub>2</sub> layer and minimize the electron-hole recombination. Finally, the broadband, effective nanohybrid photocatalyst improves the efficient electron and energy transfer among constituent components that leads to excellent photocatalytic activity. However, the direct contact of noble metal nanoparticles with upconversion materials is prejudicial to the fluorescence efficiency, because direct electron transfer or

FRET occurs.<sup>27</sup> For boosting the fluorescence emissions, a minimum distance between them should be maintained of at least 5 nm, which is propitious for decreasing the non-radiative processes and increasing the radiative decay rate.<sup>76</sup>

Other Ln<sup>3+</sup> ion-doped sodium fluoride-based phosphors such as NaGdF<sub>4</sub> and NaLuF<sub>4</sub> also have been investigated as promising frequency conversion candidates for NIR photocatalysts.<sup>77–80</sup> For example, β-NaLuF<sub>4</sub> and tetragonal-phase LiLuF<sub>4</sub> are reported as novel host matrixes that may show higher yields of upconversion efficiency than β-NaYF<sub>4</sub>,<sup>81–83</sup> ascribed to the distinctive electronic states at the top valence band of Lu<sup>3+</sup> ions and the smaller lattice-cell volume counterparts.

Besides, to construct core-shell structural upconversion nanocrystals through epitaxial growth of small lattice-mismatched



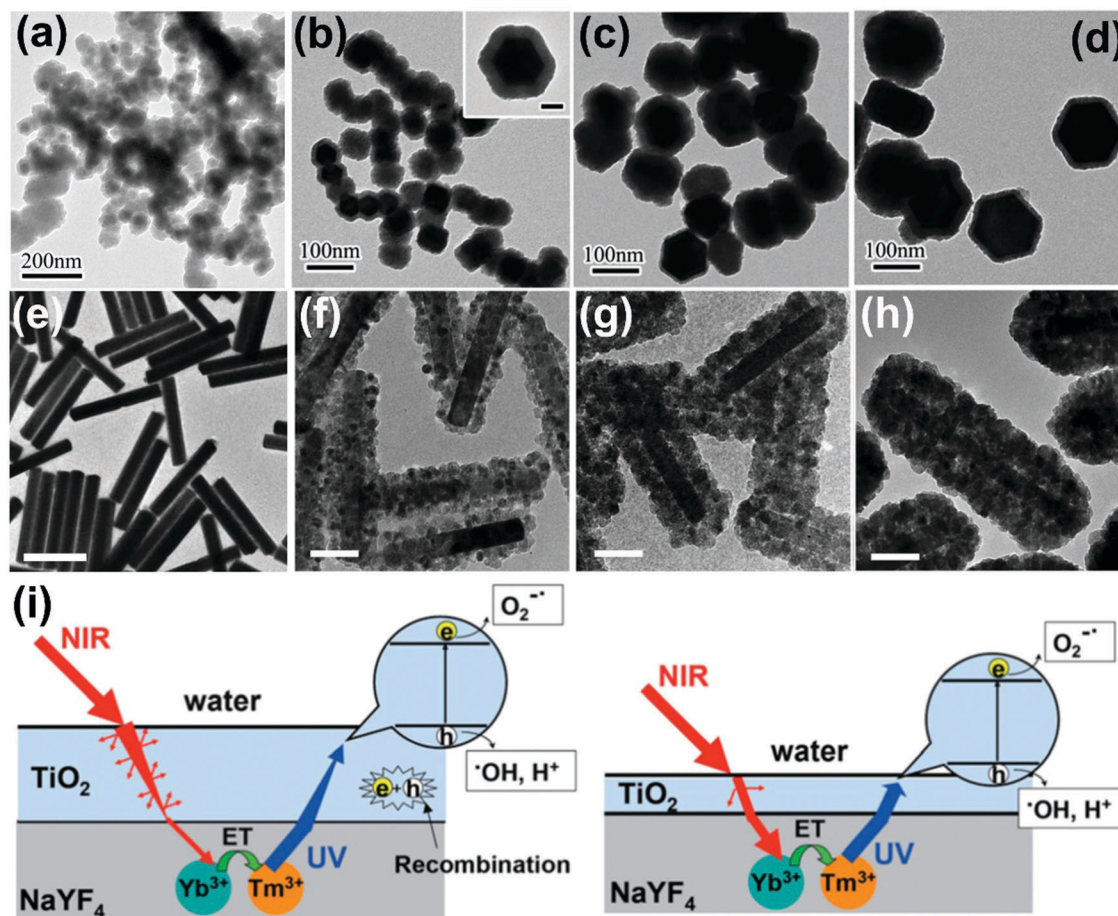


Fig. 6 TEM images of NaYF<sub>4</sub>:Yb,Tm nanoplates of different sizes: (a) 30 nm, (b) 50 nm, (c) 100 nm, (d) 130 nm covered with amorphous TiO<sub>2</sub> shell. (Reproduced with permission.<sup>55</sup> Copyright 2014, Royal Society of Chemistry.) TEM images of (e) NaYF<sub>4</sub>:Yb<sup>3+</sup>,Tm<sup>3+</sup> microrods and (f–h) NaYF<sub>4</sub>:Yb<sup>3+</sup>,Tm<sup>3+</sup>@TiO<sub>2</sub> composites with different thickness of TiO<sub>2</sub> shell (scale bars: (e) 1 μm, (f–h) 100 nm). (Reproduced with permission.<sup>57</sup> Copyright 2013, Royal Society of Chemistry.) (i) The effect of various TiO<sub>2</sub> shells on photocatalytic mechanisms (left: thick shell; right: moderate shell). (Reproduced with permission.<sup>57</sup> Copyright 2013, Royal Society of Chemistry.)

layers is excepted as a fascinating approach for improving the upconversion features, by reducing the non-radiative decay losses. The outer layers would confine the doping ions in the interior core crystals and thus inhibit the surface energy loss, resulting in improved upconversion yields. For example, excellent upconversion efficiency improvements of about 7- and 79-fold were realized after epitaxial coating of NaYF<sub>4</sub> shell on the NaYF<sub>4</sub>:Yb,Er(Tm) core, respectively.<sup>84</sup> Attributed to valid surface passivation, Huang *et al.* achieved record high upconversion quantum yield of 7.6% for LiLuF<sub>4</sub>:Yb,Tm@LiLuF<sub>4</sub> core/shell upconversion nanoparticles.<sup>81</sup> Until now, there are only two studies applied to the core/shell structured NaYF<sub>4</sub>:Yb/Tm@NaYF<sub>4</sub> and NaYF<sub>4</sub>:Tm/Yb@Yb/Nd luminescent cores as energy transducers that combine with TiO<sub>2</sub> semiconductor for environmental purification.<sup>85,86</sup> Therefore, there are still bright prospects for development of core/shell upconversion nanoparticles for photocatalytic application.

#### 4.3 The fluoride-based upconversion photocatalysts

Because of the closely arranged energy gaps of Ln<sup>3+</sup> ions, host matrixes with low photonic energy are needed to overcome the non-radiative loss between the excited levels for realizing

sensitive fluorescent transitions. Yttrium fluoride (YF<sub>3</sub>) takes advantage of low vibration energy ( $\sim 355\text{ cm}^{-1}$ ) that could reduce the quenching of electron transitions within the 4f shell, and has been selected as an appropriate candidate for matrix materials.<sup>25</sup> A model of the orthorhombic YF<sub>3</sub> structure is displayed in Fig. 8a, where the Ln<sup>3+</sup> ions will mainly occupy the interstitial sites of YF<sub>3</sub> crystals at low doping concentration and substitute the sites of Y<sup>3+</sup> ions at high doping concentration.<sup>87,88</sup> Various trivalent lanthanide ion-doped YF<sub>3</sub> crystals with micro- and nanostructural morphologies (Fig. 8b–h) have been synthesized with hydrothermal process, reverse micelle method, thermal decomposition method, micro-emulsion method and microwave method by alternatively parameterizing the reaction conditions.<sup>89–93</sup> Additionally, the sizes, morphologies and phases could be manipulated for colorful emitting luminescence properties of Ln<sup>3+</sup> ion-doped YF<sub>3</sub> nanocrystals which could act as frequency conversion elements for wide application in NIR-driven photocatalysis.

Also, Ln<sup>3+</sup> ion-doped fluoride nanocrystals are coupled with conventional semiconductors to fabricate NIR-active photocatalysts.<sup>94</sup> For instance, peanut-like YF<sub>3</sub>:Yb<sup>3+</sup>,Tm<sup>3+</sup> nanocrystals

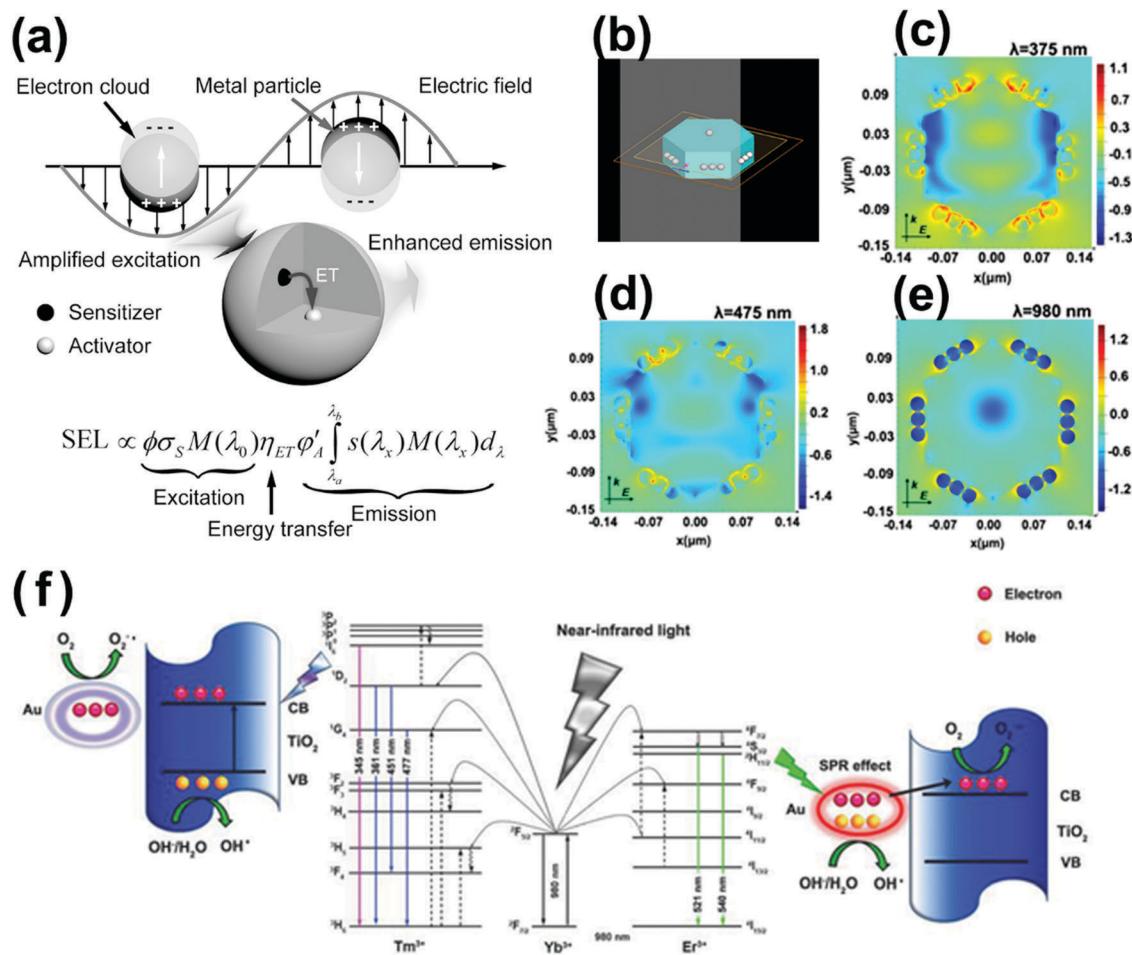


Fig. 7 (a) Plausible mechanism for plasmonic enhancement of upconversion emissions. (Reproduced with permission.<sup>27</sup> Copyright 2014, John Wiley and Sons.) (b–e) FDTD-calculated local electric field enhancement for NaYF<sub>4</sub>@SnO<sub>2</sub>@Ag nanoparticles at different incident wavelengths of 375, 475 and 980 nm. (Reproduced with permission.<sup>72</sup> Copyright 2017, American Chemical Society.) (f) Schematic photocatalytic mechanism of NYF@TiO<sub>2</sub>-Au under NIR excitation. (Reproduced with permission.<sup>71</sup> Copyright 2015, John Wiley and Sons.)

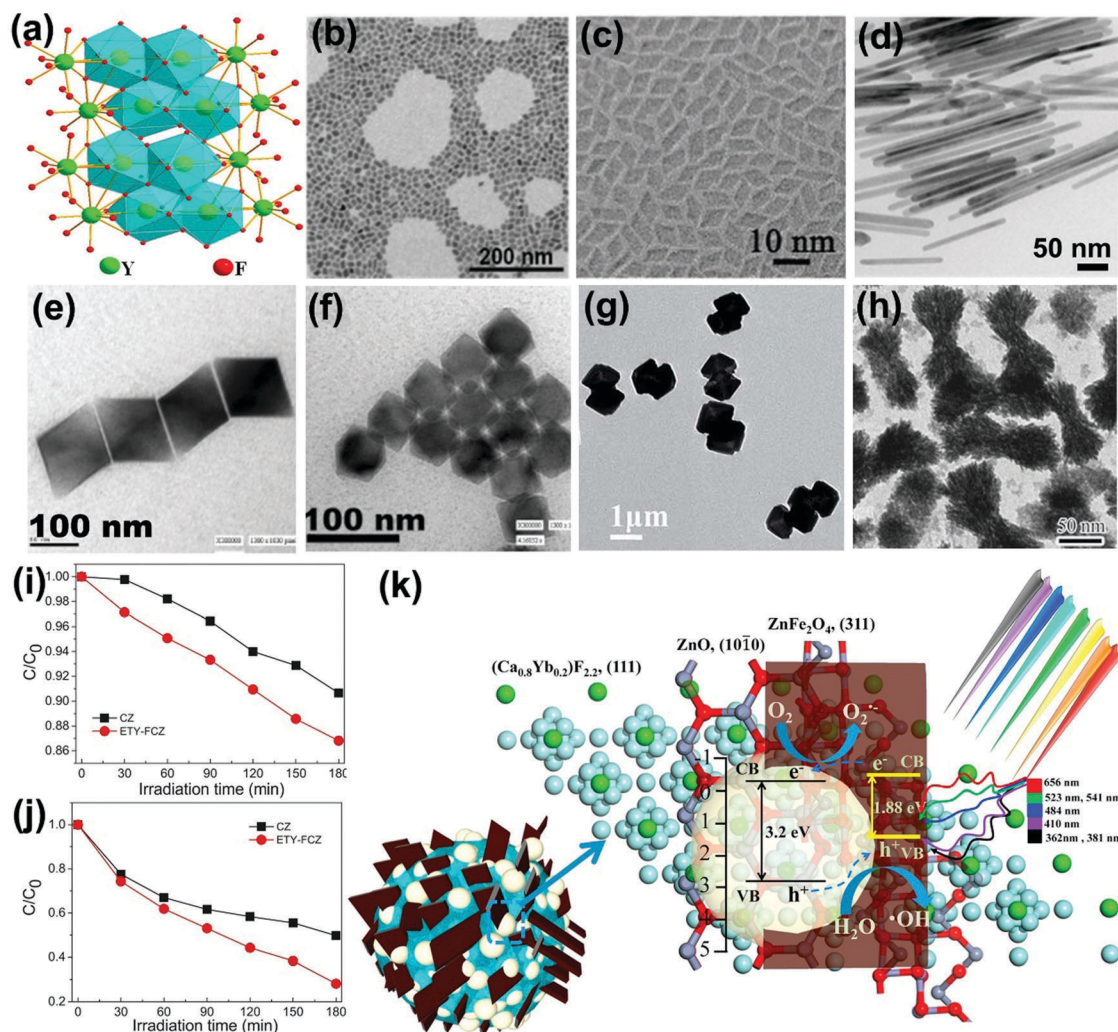
with high specific surface were coated with uniform TiO<sub>2</sub> shell, expanding the light utilization threshold to the NIR region.<sup>95</sup> Bi<sup>3+</sup> ions were further doped in YF<sub>3</sub> by substituting Y<sup>3+</sup> ions to tailor the energy transfer process between Yb<sup>3+</sup> with Er<sup>3+</sup>/Tm<sup>3+</sup>. The Bi<sup>3+</sup> ions possessing larger ionic radius will increase the cell volume of matrixes and adjust the crystal field symmetry, therefore prolonging the lifetimes of the metastable energy states by changing their wave functions, and finally enhancing the upconversion emissions.<sup>96,97</sup> Additionally, the vacancies and point defects in Ln<sup>3+</sup> ion-doped calcium fluoride (CaF<sub>2</sub>) matrix will induce charge compensation effects, thus increasing the energy transfer rates and the upconversion probability.<sup>98,99</sup> The non-toxic, stable, abundant and nonhygroscopic features of CaF<sub>2</sub> have received increasing attention in fabrication of NIR-driven photocatalysts.<sup>100–105</sup> For example, by integrating Er<sup>3+</sup>/Tm<sup>3+</sup>/Yb<sup>3+</sup> tri-doped CaF<sub>2</sub> nanocrystal with magnetic ZnFe<sub>2</sub>O<sub>4</sub> and ZnO, a multi-component and multi-functional NIR photocatalyst, ETY-FCZ, was fabricated.<sup>104</sup> The ETY-FCZ presents continuous degradation of salicylic acid (SA) (Fig. 8i) and MO (Fig. 8j) with 71.9% and 43.73% removal rates when

exposed to visible-NIR light irradiation for 180 min, respectively. Fig. 8k presents the proposed photocatalytic mechanism of the ETY-FCZ system, where the upconversion emitted UV-visible photons boosted the generation rates of electron-hole pairs of the ZnO-ZnFe<sub>2</sub>O<sub>4</sub> heterostructures. Examples of fluoride-based upconversion photocatalysts based on the recent literature are presented in Table 3.

#### 4.4 The RE sesquioxide-based upconversion photocatalysts

Although the phonon energy of RE sesquioxide materials (Y<sub>2</sub>O<sub>3</sub>, Gd<sub>2</sub>O<sub>3</sub>, Lu<sub>2</sub>O<sub>3</sub>, La<sub>2</sub>O<sub>3</sub>, etc.) is high, their excellent chemical/thermal stability makes them promising luminescence matrix candidates. Y<sub>2</sub>O<sub>3</sub> is regarded as the best sesquioxide matrix for lanthanoids with smallest phonon energy (~380 cm<sup>-1</sup>) among other metallic oxides and similar ionic radius (90 pm) to lanthanide elements. The ionic radii of Ln<sup>3+</sup> are listed in Table 4, where the ionic radii (assuming six-coordination) reduce from 106.1 pm for La<sup>3+</sup> ions to 84.8 pm for Lu<sup>3+</sup> ions accompanied with an increase of atomic number. The similar ionic radii of Ln<sup>3+</sup> ions to host cations will hinder the





**Fig. 8** (a) Schematic representation of orthorhombic structure. (Reproduced with permission.<sup>87</sup> Copyright 2017, American Chemical Society.) Typical  $\text{YF}_3$  morphologies of (b) nanospheres (reproduced with permission;<sup>88</sup> copyright 2014, Royal Society of Chemistry), (c) rhombic shapes (reproduced with permission;<sup>89</sup> copyright 2014, Royal Society of Chemistry), (d) nanorods (reproduced with permission;<sup>91</sup> copyright 2017, American Chemical Society), (e) quadrilateral-shaped particles (reproduced with permission;<sup>90</sup> copyright 2005, American Chemical Society), (f) hexagonal particles (reproduced with permission;<sup>90</sup> copyright 2005, American Chemical Society), (g) dumbbell-shaped particles (reproduced with permission;<sup>92</sup> copyright 2017, Royal Society of Chemistry) and (h) peanut-like nanocrystals (reproduced with permission;<sup>95</sup> copyright 2013, Elsevier BV). The photocatalytic performances of as-fabricated NIR-driven photocatalyst ETY-FCZ for degradation of (i) SA and (j) MO, and (k) the proposed photocatalytic mechanism (reproduced with permission;<sup>104</sup> copyright 2015, Elsevier BV).

generation of crystal defects and lattice stress, and thus facilitating the upconversion efficiency.<sup>106</sup> More importantly, the distance of interacting ions ( $D$ ) dominates the electric dipole-dipole energy transfer efficiency ( $P$ ) between sensitizer and activator ions, which follows the relationship:<sup>107</sup>

$$P \sim \frac{1}{D^6} \quad (3)$$

where the nearest interaction distances of RE ions confined in the host lattice of  $\text{Y}_2\text{O}_3$ ,  $\text{Gd}_2\text{O}_3$ ,  $\text{Lu}_2\text{O}_3$  and  $\text{La}_2\text{O}_3$  are presented in Table 5. Comparatively, it can be predicted that a more efficient energy transfer could be achieved with the same lanthanide dopants in the  $\text{Lu}_2\text{O}_3$  host than in the  $\text{Gd}_2\text{O}_3$  and  $\text{La}_2\text{O}_3$  hosts, and their upconversion efficiency may obey the

sequence of  $\text{Lu}_2\text{O}_3 > \text{Gd}_2\text{O}_3 > \text{La}_2\text{O}_3$ . As mentioned above, the low vibration energy of  $\text{Y}_2\text{O}_3$  matrix improves the probability of radiative transitions among electronic energy levels of lanthanide dopants, inducing the highest interacting energy transfer rate in sesquioxides.

Schematic illustrations of RE sesquioxide unit cells modeled according to the structural parameters in Table 5 are shown in Fig. 9.<sup>108–110</sup> The nanocrystalline systems of  $\text{RE}_2\text{O}_3$  (RE = Y, Gd, Lu) prefer the formation of cubic structure with space group of  $Ia\bar{3}$  (No. 206) (Fig. 9a and b), while  $\text{La}_2\text{O}_3$  is predisposed to unconventional hexagonal phase with space group of  $P3m1$  (No. 164) (Fig. 9c and d). Theoretically, the polymorphism of RE sesquioxides with lighter atoms (La–Sm) generally means that they adopt the hexagonal structure and the heavier atoms



Table 3 Photodegradation performances of fluoride-based semiconductor photocatalysts

| Photocatalyst (mg)                                                                | Light source                          | Pollutants (concentration, mg L <sup>-1</sup> /volume, mL) | Degradation ratio/time (min) | Ref. |
|-----------------------------------------------------------------------------------|---------------------------------------|------------------------------------------------------------|------------------------------|------|
| YF <sub>3</sub> :Yb,Tm/TiO <sub>2</sub> (0.5)                                     | 1.5 W 980 nm laser                    | MB (15/0.5)                                                | 70%/1800                     | 94   |
| YF <sub>3</sub> :Yb,Tm@TiO <sub>2</sub> (20)                                      | 50 W Xe lamp                          | MO (50/20)                                                 | 85%/70                       | 95   |
| NaY(WO <sub>4</sub> ) <sub>2</sub> /TiO <sub>2</sub> /YF <sub>3</sub> :Yb,Tm (20) | 1000 W mercury lamp                   | MO (10/20)                                                 | 100%/60                      | 96   |
|                                                                                   |                                       | SA (10/20)                                                 | 90%/60                       |      |
| CaF <sub>2</sub> :Er,Yb@TiO <sub>2</sub> (50)                                     | 500 W Xe lamp (720 nm < λ < 1 100 nm) | MB (10/50)                                                 | 60%/720                      | 100  |
|                                                                                   |                                       | MO (10/50)                                                 | 32%/720                      |      |
| BiVO <sub>4</sub> /CaF <sub>2</sub> :Er,Tm,Yb (0.5)                               | 980 nm laser (10 W cm <sup>-2</sup> ) | MB (15/0.5)                                                | 75%/420                      | 101  |
| CaWO <sub>4</sub> @(TiO <sub>2</sub> /CaF <sub>2</sub> :Er/Tm/Yb) (20)            | 980 nm laser (2 A)                    | MO (10/20)                                                 | 20.29%/180                   | 102  |
|                                                                                   | 1000 W mercury lamp (λ ≥ 780 nm)      |                                                            | 46.57%/180                   |      |
| CaWO <sub>4</sub> @(TiO <sub>2</sub> /CaF <sub>2</sub> :Er/Tm/Yb) (20)            | 980 nm laser (2 A)                    | MO (10/20)                                                 | 20.29%/180                   | 103  |
|                                                                                   | 1000 W mercury lamp                   |                                                            | 99.02%/60                    |      |
| CaF <sub>2</sub> :Er/Tm/Yb@ZnFe <sub>2</sub> O <sub>4</sub> /ZnO (20)             | 1000 W mercury lamp (λ ≥ 400 nm)      | MO (10/20)                                                 | 71.9%/180                    | 104  |
|                                                                                   |                                       | SA (10/20)                                                 | 43.73%/180                   |      |
| CaF <sub>2</sub> :Yb@BiVO <sub>4</sub> (20)                                       | 980 nm laser (2 A)                    | MO (10/10)                                                 | 10%/360                      | 105  |
|                                                                                   | 1000 W mercury lamp                   |                                                            | 41%/180                      |      |

Table 4 The ionic radii of Ln<sup>3+</sup>

| Element                                             | La    | Ce    | Pr    | Nd   | Pm   | Sm   | Eu   | Gd   |
|-----------------------------------------------------|-------|-------|-------|------|------|------|------|------|
| Atomic number                                       | 57    | 58    | 59    | 60   | 61   | 62   | 63   | 64   |
| Ionic radius <sup>a</sup> (10 <sup>-12</sup> m, pm) | 106.1 | 103.4 | 101.3 | 99.5 | 97.9 | 96.4 | 94.7 | 93.8 |

| Element                                | Tb   | Dy   | Ho   | Er   | Tm   | Yb   | Lu   | — |
|----------------------------------------|------|------|------|------|------|------|------|---|
| Atomic number                          | 65   | 66   | 67   | 68   | 69   | 70   | 71   | — |
| Ionic radius (10 <sup>-12</sup> m, pm) | 92.3 | 91.2 | 90.1 | 88.1 | 86.9 | 85.8 | 84.8 | — |

<sup>a</sup> Assuming six-coordination.

(Ho–Lu) prefer the cubic, whereas the intermediate atoms (Sm–Dy) can be stabilized in both cubic and monoclinic structures (Fig. 9e).<sup>108</sup> The lighter Ln<sup>3+</sup> ions with larger ionic radii prefer the formation of hexagonal crystals in virtue of higher electron cloud distortion induced by increased dipole polarizability.<sup>42</sup> The results will offer us reasonable guidance for accommodating appropriate Ln<sup>3+</sup> dopants in morphological construction engineering.

RE sesquioxide nanocrystals incorporated with semiconductors were employed for synthesis of photocatalysts for environmental cleaning and energy conversion.<sup>111–116</sup> For example, the Yb<sup>3+</sup>,Tm<sup>3+</sup> co-doped Y<sub>2</sub>O<sub>3</sub> upconversion luminescence agent was composited with TiO<sub>2</sub> and showed higher infrared-to-UV photocatalytic activity than non-doped TiO<sub>2</sub>

under irradiation of solar light.<sup>114</sup> Another chain-like Er/Tm/Yb/Y<sub>2</sub>O<sub>3</sub> composite demonstrated higher upconversion luminescent intensity than flake-like Er/Tm/Yb/Y<sub>2</sub>O<sub>3</sub> upconversion nanoparticles, leading to better photocatalytic performance for degradation of MB dyes when coupling with 3C-SiC nanocrystals.<sup>113</sup> Furthermore, the Gd<sup>3+</sup> ions with magnetic properties are used to fabricate optically and magnetically active bifunctional materials for advanced multifunctional photocatalysts.<sup>112,117</sup>

#### 4.5 The Ln<sup>3+</sup> ion-doped upconversion photocatalysts

In recent years, the doping of ions into a semiconductor matrix, including non-metal ions (P<sup>3-</sup>, S<sup>2-</sup>, Cl<sup>-</sup>, etc.) and metal ions (Zn<sup>2+</sup>, Cu<sup>2+</sup>, Fe<sup>3+</sup>, etc.), has become popular and a prime motivation to extend the optical absorption threshold, or trap the photogenerated electrons by induced oxygen vacancy and/or surface defect, finally improving the photoactivities.<sup>4,9,118,119</sup> Similarly, the current strategies of doping with Ln<sup>3+</sup> ions into semiconductors such as TiO<sub>2</sub>, ZnO, BiVO<sub>4</sub>, etc., have proved to be an interesting and not yet fully explored highway for optimizing the photocatalytic performance.<sup>120–128</sup> As displayed in Fig. 10, 4f orbital electronic states of Ln<sup>3+</sup> ions bring the sub-bandgap levels that settled down below the conduction band edge of semiconductors. The electrons will populate the inserted electronic states of Ln<sup>3+</sup> ions instead of intrinsic conduction

Table 5 Structural parameters of RE<sub>2</sub>O<sub>3</sub> (RE: Y, La, Gd, Lu) nanocrystals

| Hosts                                               | Y <sub>2</sub> O <sub>3</sub> | Gd <sub>2</sub> O <sub>3</sub>   | Lu <sub>2</sub> O <sub>3</sub>   | La <sub>2</sub> O <sub>3</sub>   |
|-----------------------------------------------------|-------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Phonon energy (cm <sup>-1</sup> )                   | ~380                          | ~600                             | ~618                             | ~400                             |
| Bandgap (eV)                                        | 5.6                           | 5.4                              | 6                                | 5.5                              |
| Ionic radius <sup>a</sup> (10 <sup>-12</sup> m, pm) | 90                            | 93.8                             | 84.8                             | 106.1                            |
| Crystal system                                      | Cubic                         | Cubic                            | Cubic                            | Hexagonal                        |
| Space group                                         | Ia $\bar{3}$ (206)            | Ia $\bar{3}$ (206)               | Ia $\bar{3}$ (206)               | P $\bar{3}m1$ (164)              |
| Lattice parameters                                  | a = b = c = 10.6073 Å         | a = b = c = 10.8012 Å            | a = b = c = 10.3946 Å            | a = b = 3.9198 Å<br>c = 6.1139 Å |
|                                                     | α = β = γ = 90°               | α = β = γ = 90°                  | α = β = γ = 90°                  | α = β = 90°, γ = 120°            |
| Nearest RE distance (Å)                             | 3.52 (Y1–Y2)<br>3.53 (Y2–Y2)  | 3.59 (Gd1–Gd2)<br>3.61 (Gd2–Gd2) | 3.44 (Lu1–Lu2)<br>3.46 (Lu2–Lu2) | 3.83 (La–La)                     |

<sup>a</sup> Assuming six-coordination.

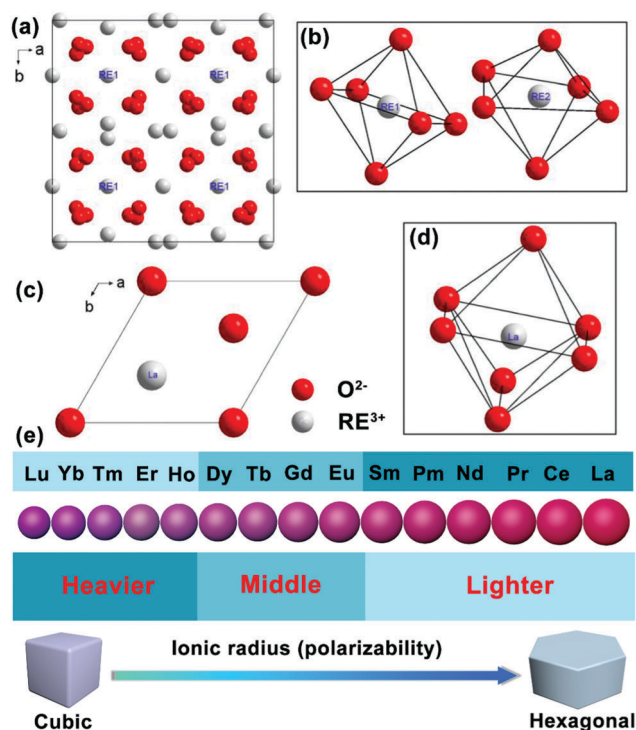


Fig. 9 Schematic illustration of the unit cell projected on  $a$ - $b$  plane and the RE coordination polyhedra: (a and b)  $\text{RE}_2\text{O}_3$  (RE = Y, Gd, Lu), (c and d)  $\text{La}_2\text{O}_3$  (reproduced with permission;<sup>108</sup> copyright 2018, Elsevier BV). (e) Ionic radius (or polarizability) induced phase transition from cubic to hexagonal of  $\text{Ln}^{3+}$  ion-doped upconversion crystals.

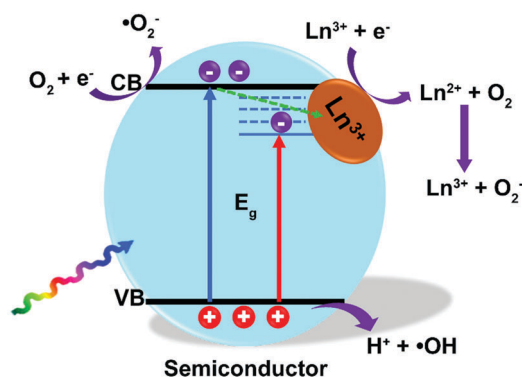


Fig. 10 Photocatalytic mechanism of  $\text{Ln}^{3+}$ -doped semiconductor photocatalysts.

band edge of semiconductors, thus narrowing the bandgap energy of photocatalysts and extending the optical absorption threshold.<sup>129,130</sup> For example, the bandgap energy values of  $\text{B-BiVO}_4$  with different doping concentrations of  $\text{Eu}^{3+}$  ions varied from 0 to 1.0% were calculated by using the Kubelka-Munk function. The bandgaps were tailored from 2.36 eV to 2.26 eV by raising the dopant dosage of  $\text{Eu}^{3+}$  ions, inducing approximately nine times higher photocatalytic activity (0.8  $\text{Eu-BiVO}_4$ ) compared with pure  $\text{BiVO}_4$ .<sup>131</sup>

Additionally, the lanthanides are well known for being capable of forming complexes with a variety of Lewis bases,

like amines, aldehydes, alcohols, and thiols, taking advantage of their functional groups and the f-orbitals of the lanthanoids.<sup>34,132</sup> Meanwhile, the substitution of high valence state ions (such as  $\text{Ti}^{4+}$ ) with trivalent  $\text{Ln}^{3+}$  ions will break the charge balance, which may be compensated by negative functional groups of dyes.<sup>133</sup> This is desirable to increase the adsorption capacity of organic dyes with photocatalysts due to the negative functional group, therefore laying good preparatory foundations for subsequent photocatalytic reactions.<sup>134</sup> For example, three-fold higher adsorption constants  $k$  were achieved in  $\text{Pr}^{3+}/\text{Eu}^{3+}$  ion-doped  $\text{TiO}_2$  photocatalysts that were analyzed according to Langmuir's theory.<sup>135</sup> The  $\text{Ln}^{3+}$  sites can act as electron acceptors to trap the photogenerated electrons and minimize undesired electron-hole recombination, where the trapped electrons are capable of combining with oxygen to form superoxide radicals for photo-oxidation of adsorbed organics. Especially, for  $\text{Gd}^{3+}$  ions with special half-filled electronic configuration of 7f-electrons, it is easier to transfer the trapped electrons to the interfacial adsorbed oxygen.<sup>130,136</sup>

It is well known that doping of  $\text{Ln}^{3+}$  ions will improve the photocatalytic performance of semiconductors by regulating the band energy and promoting the separation of carriers. Meanwhile, the loading concentration and type of  $\text{Ln}^{3+}$  dopant ions are also important parameters that affect the photocatalytic performance. High dopant dosage will increase the surface barrier of the semiconductors and decrease the space charge region. A large electric field is beneficial for promoting the separation of photoinduced carriers. But if the doping concentration is too high, the space charge region will become narrow that substantially reduces the penetration depth of light into semiconductors, and hence greatly increases the recombination possibilities of photoinduced carriers.<sup>130,137</sup> Moreover, owing to the generally large ionic radii of  $\text{Ln}^{3+}$  ions (Table 4), for example, larger than  $\text{Ti}^{4+}$  ( $\sim 68$  pm), small and isolated clusters of lanthanide oxide will form and cover the surface of semiconductors at high doping concentration, which will aggregate as carrier capture centers, thus deactivating the photocatalytic activity.<sup>138</sup> Therefore, there must be an optimum concentration level of dopants to balance the thickness of the space charge layer substantially equivalent to the light penetration depth. For instance,  $\text{La}^{3+}$  ion-doped  $\text{TiO}_2$  at a concentration of 0.5% was proved to possess the most efficient photodegradation rate for MO counterparts.<sup>139</sup> And  $\text{Dy}^{3+}$ -doped  $\text{ZnO}$  nanoparticles with a doping concentration of 3% were found to endow the highest decolorization efficiency of C. I. Acid Red 17 under visible light irradiation.<sup>140</sup>

In the activator ion (*i.e.*,  $\text{Tm}^{3+}$ ,  $\text{Er}^{3+}$ ) and sensitizer ion (*i.e.*,  $\text{Yb}^{3+}$ ,  $\text{Nd}^{3+}$ ) co-doped semiconductor system, the sensitizer will accept the NIR photons and transfer the energy to the nearest activator ions for emitting UV-visible photons by the upconversion process. As mentioned above, the upconverted photons favor the donation to the valence band of semiconductor followed by oxidative hole ( $h^+$ ) generation by extraction of a reductive electron, thus boosting the yield of photocarriers and improving the photocatalytic efficiency.<sup>141,142</sup>

## 5. Outlooks and perspectives

In summary, the synthesis of upconversion materials with effective quantum yields and fabrication of upconversion-based semiconductor photocatalysts are considerable challenges. Despite the significant developments in this direction, there are several tough challenges associated with upconversion materials that limit their applications in basic sciences, including lower upconversion yields and confined excitation wavelengths. However, the reported highest upconversion efficiency is  $3.0 \pm 0.3\%$  for  $\text{Yb}^{3+}, \text{Er}^{3+}$  co-doped bulk  $\text{NaYF}_4$  materials.<sup>143</sup> Nevertheless, the micro- or nanomaterials possess lower upconversion efficiency than bulk materials because of the synergistic effect of surface state defects induced by the small particle sizes and adhering water reducing the optical efficiency. Therefore, much effort is required to design and develop high-efficiency upconversion materials. To achieve this purpose, the first method is to select host materials with low phonon energy, which prefer to decrease multi-phonon relaxation between closely spaced energy levels, thus generating more effective upconversion. The host materials provide a surrounding crystalline field for  $\text{Ln}^{3+}$  ions but do not determine the emissions. The type of lanthanide dopant and doping concentration are vital for tailoring the upconverted luminescence. In addition, the SPR effect of noble metals is proved theoretically and experimentally to boost the upconversion luminescence by enhancing the absorption of the sensitizer through electric-field coupling, improving the radiative decay rate of the activator, and increasing energy transfer from the sensitizer to the activator. The intrinsic features of SPR are greatly beneficial to the photocatalytic performance of semiconductor photocatalysts by boosting the yield of photogenerated electron/hole pairs and promoting their effective separation. In addition, the SPR of noble metal nanoparticles could effectively promote the efficiency of upconversion materials. Interestingly, researchers have recently discovered localized surface plasmon resonances (LSPRs) in heavily doped semiconductor nanoparticles, quantum dots and amorphous two-dimensional nanomaterials.<sup>144–146</sup> The occurrence of LSPR originates from collective oscillations of excess free carriers, the concentration of which ( $10^{19}$ – $10^{21} \text{ cm}^{-3}$ ) can be regulated by adjusting stoichiometric ratios, vacancy or doping concentrations, phase structures, *etc.*<sup>147</sup> Therefore, the LSPR-induced electric field in semiconductors provides a powerful strategy to enhance the upconversion efficiency. More importantly, the unique interactions based on the process of plasmonic energy transfer will further improve the NIR light-active photocatalytic performance.<sup>148,149</sup> The marriage of upconversion with semiconductor LSPR could be a novel frontier in fundamental investigations and practical solar energy conversion applications.

Also, epitaxial growth of a shell with small lattice mismatch around a core can reduce non-radiative decay losses of the surface fluorescence, which would offer a useful way to improve the fluorescence intensity of upconversion crystals. In a core-shell structure, the dopant RE ions are incorporated into the interior core layer of particles. The shell layer can effectively

suppress energy loss on the crystal surface, resulting in higher luminescence efficiency. These attractive features of core-shell structures make them suitable candidates for photocatalytic application.

The preceding discussion is concentrated entirely on  $\text{Yb}^{3+}$  ion (absorption cross section  $\approx 10^{-20} \text{ cm}^2$ )-sensitized upconversion materials with the photo-absorption band centered at 980 nm. By paying attention to the drawbacks of confined excitation wavelength, innovative strategies that incorporate replaceable sensitizers have been proposed for tuning the excitation wavelengths of upconversion crystals.  $\text{Nd}^{3+}$  is ideal as an alternative sensitizer since it has a one order of magnitude larger absorption cross section ( $\approx 10^{-19} \text{ cm}^2$ ) at  $\approx 800 \text{ nm}$  than  $\text{Yb}^{3+}$  at  $\approx 980 \text{ nm}$ .<sup>27</sup> Benefiting from the unique features of deep tissue penetration depth and low photothermal effect of  $\approx 800 \text{ nm}$  light (first NIR window), the  $\text{Nd}^{3+}$ -sensitized upconversion nanoparticles have attracted considerable interdisciplinary attention in biosensing, bioimaging, drug delivery, therapy, and three-dimensional displays.<sup>150</sup> Unfortunately, there is no literature focusing on the  $\text{Nd}^{3+}$ -sensitized upconversion materials as energy conversion elements that are composited with semiconductor photocatalysts, for further utilizing solar light centered at 800 nm. The emergence of  $\text{Nd}^{3+}$ -sensitized upconversion nanoparticles would open other possible avenues of future works on upconversion semiconductor-based photocatalytic systems. We anticipate new breakthroughs in the construction of novel and highly efficient NIR-light-activated photocatalysts.

At present, almost all the considered NIR light-active photocatalytic systems are applied in organic dye degradation. It will be of significant importance to exploit potential effective photocatalysts for solving the challenges faced by the community of upconversion-based materials for their more efficient and wider applications to energy production and storage such as water splitting,  $\text{CO}_2$  conversion, *etc.*<sup>151,152</sup>

## Author contributions

All authors contributed during the preparation of the manuscript. All authors have given approval to the final version of the manuscript.

## Conflicts of interest

The authors declare that they have no competing interests.

## Acknowledgements

This work was supported by the NSFC (51471121), Hubei Provincial Natural Science Foundation (2014CFB261), Basic Research Plan Program of Shenzhen City (JCYJ20160517104459444), Natural Science Foundation of Jiangsu Province (BK20160383) and Wuhan University.



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