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Enhanced upconversion and photoconductive nanocomposites of lanthanide-doped nanoparticles functionalized with low-vibrational-energy inorganic ligands†

Jia-Ahn Pan,^a Xiao Qi^b and Emory M. Chan^{a,b}

Upconverting nanoparticles (UCNPs) convert near-infrared (IR) light into higher-energy visible light, allowing them to be used in applications such as biological imaging, nano-thermometry, and photo-detection. It is well known that the upconversion luminescent efficiency of UCNPs can be enhanced by using a host material with low phonon energies, but the use of low-vibrational-energy inorganic ligands and non-epitaxial shells has been relatively underexplored. Here, we investigate the functionalization of lanthanide-doped NaYF₄ UCNPs with low-vibrational-energy Sn₂S₆^{4−} ligands. Raman spectroscopy and elemental mapping are employed to confirm the binding of Sn₂S₆^{4−} ligands to UCNPs. This binding enhances upconversion efficiencies up to a factor of 16, consistent with an increase in the luminescent lifetimes of the lanthanide ions. Annealing Sn₂S₆^{4−}-capped UCNPs results in the formation of a nanocomposite comprised of UCNPs embedded within an interconnected matrix of SnS₂, enabling each UCNP to be electrically accessible through the semiconducting SnS₂ matrix. This facilitates the integration of UCNPs into electronic devices, which we demonstrate through the fabrication of a UCNP–SnS₂ photodetector that detects UV and near-IR light. Our findings show the promise of using inorganic capping agents to enhance the properties of UCNPs while facilitating their integration into optoelectronic devices.

Introduction

Lanthanide-doped upconverting nanoparticles (UCNPs) are nanoscale colloidal light emitters that absorb multiple low-energy photons and emit a higher-energy photon.^{1–11} This optical

New concepts

We introduce low-vibrational-energy inorganic ligands that enhance the luminescence of lanthanide-doped upconverting nanoparticles (UCNPs) and enable their integration into electronic devices. Existing ligand approaches typically employ UCNPs that are either (1) capped with organic/polymer ligands that have high vibrational energies or (2) ligand-free, leaving no protective barrier between the UCNP and the environment. Our method utilizes metal sulfide ions to charge-stabilize UCNPs and create a favorable environment that minimizes non-radiative quenching. Additionally, these inorganic ligand-capped UCNPs can be annealed to form a UCNP–semiconductor nanocomposite in which UCNPs are embedded within a non-epitaxial matrix, facilitating interfacing with other electronic components. To validate this approach, we incorporate the UCNP–semiconductor composite as the active layer in a photodetector capable of detecting UV and near-IR light. This inorganic ligand-to-matrix approach complements epitaxial shell growth, which is electrically insulating and often requires stringent growth conditions. Our findings demonstrate a new ligand-based strategy for enhancing the optical performance of UCNPs and expanding their applicability in optoelectronics.

property, known as upconversion luminescence (UCL), is enabled by the ladder-like energy levels of lanthanide ions doped within an inorganic host matrix. With their tunable optical properties and precise nanoscale size control, UCNPs have been used for applications such as biological imaging,⁴ nano-thermometry,⁵ super-resolution microscopy,^{6,7} lithography,⁸ optical computing,^{9,10} and photodetection.¹¹

The most common way to achieve efficient UCL from lanthanide ions is to embed them in inorganic host matrices such as NaYF₄ and K₂Pb₂Cl₅, whose low phonon energies reduce phonon-assisted non-radiative relaxation.^{12,13} UCL efficiency can be further enhanced by growing an undoped, epitaxial shell made of the same material, allowing the active lanthanide ions to be optically and chemically isolated from their environments. However, while the chemistry for growing high-quality epitaxial shells has been optimized for some UCNP host materials (e.g., NaYF₄),¹⁴ the growth of epitaxial shells for other host materials (e.g., K₂Pb₂Cl₅) can be more challenging

^a Department of Natural Sciences, Pitzer and Scripps Colleges, Claremont, California, 91711, USA. E-mail: jpan@natsci.claremont.edu

^b Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA. E-mail: emchan@lbl.gov

^c Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

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and remains an active area of research. Non-epitaxial oxide shells have been grown around UCNPs, leading to increased thermal stability;¹⁵ however, their high phonon energies typically do not enhance UCL and may even reduce it.

The ligands that coordinate the surfaces of UCNPs also play an important role in their optical properties. While UCNP ligand modification has been studied primarily to maintain colloidal stability in various solvents and environments (*e.g.*, in cells),¹⁶ antenna ligands have also been used to dramatically enhance the small absorption cross-sections of UCNPs.¹⁷ Even ligands that do not absorb light can impact the photophysics of luminescent nanocrystals by introducing or suppressing non-radiative pathways.^{18,19} The UCL of UCNPs has been enhanced by small organic ligands, such as picolinic acid, which can alter the electronic structure of lanthanide dopants at the nanocrystal surfaces, demonstrating the potential of ligand engineering for UCNPs.²⁰ Ligand engineering is preferable to inert shell growth when a small size is needed (*e.g.*, cell imaging and nanoscale devices). However, the high-energy vibrational modes of common organic ligands can quench UCNP luminescence, especially in the absence of passivating inorganic shells.

As an alternative to organic ligands, ionically charged inorganic compounds have been explored as capping ligands for semiconducting QDs.²¹ These inorganic ligands, such as metal sulfide complexes, have been used to increase the electronic coupling between QDs, enhancing their performance in devices such as transistors and photodetectors.²² Additionally, these heavier inorganic ligands possess lower vibrational energies, which may help reduce nonradiative quenching of lanthanide excited states in UCNPs. However, it remains an open question whether the chemically-“soft” sulfide ligands—typically used to coordinate with the soft Lewis acid cations in QDs—are compatible with the hard lanthanide ions in UCNPs.

Here, we investigate the use of a tin(IV) sulfide complex ($\text{Sn}_2\text{S}_6^{4-}$) as a low-vibrational-energy inorganic ligand for NaYF_4 UCNPs (Scheme 1). We explored chemical approaches to replace the native oleate ligands with the $\text{Sn}_2\text{S}_6^{4-}$ ligands and confirmed the successful ligand exchange *via* Raman and energy-dispersive X-ray spectroscopy (EDS). Optically, we found that the UCL efficiencies of UCNPs were enhanced by this exchange, with the greatest enhancements observed for small and highly doped UCNPs (exhibiting UCL enhancements up to a factor of 16). We show that the $\text{Sn}_2\text{S}_6^{4-}$ ligands can be transformed into a SnS_2 matrix upon annealing at 350 °C, forming a UCNP- SnS_2 nanocomposite. Finally, we fabricate a proof-of-concept UV and NIR photodetector using the solution-deposited

UCNP- SnS_2 nanocomposite. These findings reveal a pathway for using inorganic ligands to broaden the applications of UCNPs.

Results and discussion

Functionalization of UCNPs with $\text{Sn}_2\text{S}_6^{4-}$ ligands

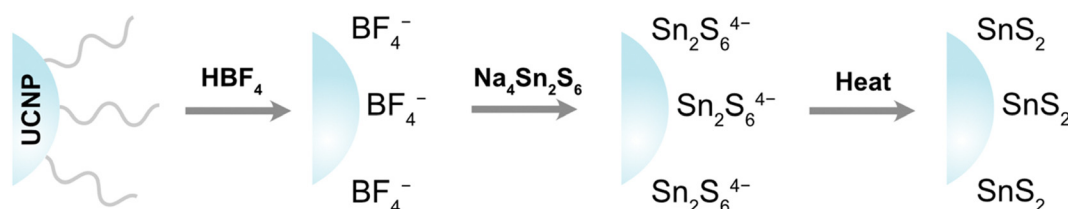
Lanthanide-doped NaYF_4 UCNPs and $\text{Na}_4\text{Sn}_2\text{S}_6$ ligands were synthesized according to established protocols (see Methods and ESI† for details).^{23,24} We initially attempted ligand exchange by directly adding $\text{Sn}_2\text{S}_6^{4-}$ ligands to a toluene dispersion of UCNPs. However, after stirring for several hours, no nanoparticle aggregation was observed, indicating that this method was ineffective in facilitating ligand exchange.

We also explored a two-phase direct exchange that involved stirring oleate-capped UCNPs in hexanes with an immiscible layer of *N*-methylformamide (NMF) containing dissolved $\text{Sn}_2\text{S}_6^{4-}$ ligands. After stirring for 24 h, the UCNPs were observed to have either aggregated at the solvent interface or in the polar phase. Upon extraction, these UCNPs were unable to be redispersed in either a non-polar hexane solution or a polar NMF solution, implying that the ligand exchange was incomplete, *i.e.*, UCNPs were only partially coated with $\text{Sn}_2\text{S}_6^{4-}$ ligands.

Our most successful direct exchange approach involved mixing oleate-capped UCNPs with $\text{Sn}_2\text{S}_6^{4-}$ ligands in NMF. After sonicating the suspension for a few hours, a small fraction of the UCNPs were observed to be dispersed in the NMF solution (with a larger fraction remaining aggregated). The aggregated UCNPs were then removed by centrifugation, leaving a supernatant of colloidally dispersed, $\text{Sn}_2\text{S}_6^{4-}$ -capped UCNPs.

Considering the challenges faced with direct ligand exchange, we hypothesized that $\text{Sn}_2\text{S}_6^{4-}$ functionalization could be improved by first removing the oleate ligands before functionalization. This two-step indirect ligand exchange process first involves stripping the oleate ligands from UCNPs using HBF_4 , resulting in bare but electrically charged UCNPs that can be dispersed in a polar solvent.⁸ Then, $\text{Sn}_2\text{S}_6^{4-}$ ligands are added to coat the bare UCNPs. We theorized that this indirect approach may be more effective since it circumvents the need for $\text{Sn}_2\text{S}_6^{4-}$ to directly displace strongly bound oleate ligands.

To evaluate the effectiveness of our ligand exchange procedures, we characterized the $\text{Sn}_2\text{S}_6^{4-}$ -capped UCNPs with Raman spectroscopy and electron microscopy. The Raman spectra of $\text{Sn}_2\text{S}_6^{4-}$ -capped NaYF_4 UCNPs obtained through direct and indirect ligand exchange approaches were similar, showing a distinct peak at 182 cm^{-1} as well as a cluster of peaks in the



Scheme 1 Ligand exchange of oleate-capped NaYF_4 UCNPs with $\text{Sn}_2\text{S}_6^{4-}$ ligands and subsequent annealing into a UCNP- SnS_2 nanocomposite.

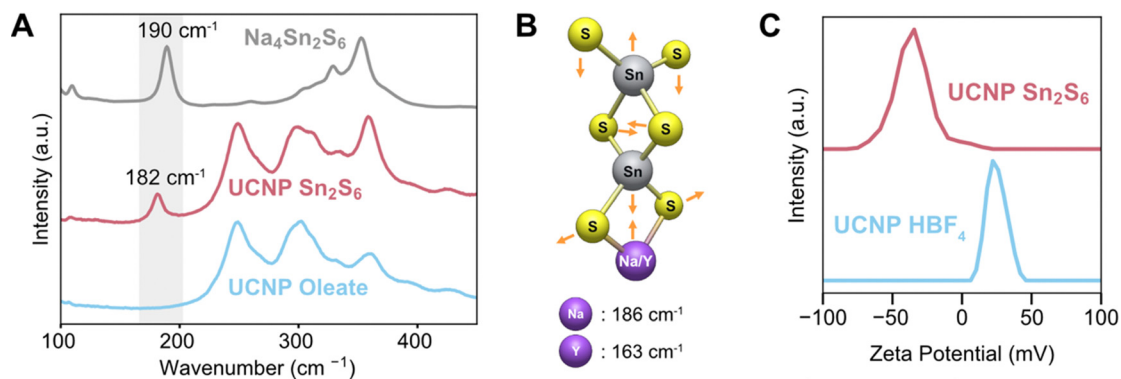


Fig. 1 (A) Raman spectra of Na₄Sn₂S₆ and 14-nm NaYF₄: 30% Yb³⁺, 0.5% Tm³⁺ UCNPs capped with oleate or Sn₂S₆⁴⁻ ligands. (B) The relevant Raman-active vibrational mode of (NaSn₂S₆)³⁻ and (YSn₂S₆)³⁻ compounds and their vibrational energies. (C) Zeta potential of 15-nm NaYF₄: 20% Yb³⁺, 2% Er³⁺ UCNPs after ligand stripping and after Sn₂S₆ binding.

region of 250–350 cm⁻¹ (Fig. 1A, red). We attribute the 182 cm⁻¹ peak to a vibrational mode of UCNP-bound Sn₂S₆⁴⁻ ligands, which is close to the 190 cm⁻¹ peak that we observe in the Raman spectrum of Na₄Sn₂S₆ (Fig. 1A, grey). On the other hand, the cluster of peaks at 250–350 cm⁻¹ can be primarily attributed to the phonon modes of hexagonal-phase NaYF₄, which were also observed in oleate-capped UCNPs (Fig. 1A, blue).²⁵ We note that Na₄Sn₂S₆ also has a strong peak around 350 cm⁻¹, but it overlaps with the NaYF₄ peaks and cannot be unambiguously determined in Sn₂S₆⁴⁻-capped NaYF₄ UCNPs.

To better understand the molecular origin of our Raman spectra, we carried out density functional theory (DFT) calculations. Since Sn₂S₆⁴⁻ and NaYF₄ have overlapping peaks in the 200–450 cm⁻¹ region, we focused our analysis on the 180–190 cm⁻¹ peak. Our DFT calculations show that this vibrational mode can be attributed to a bending mode that involves the vibration of all bonds within Sn₂S₆⁴⁻ as well as its bonds to the metal ion. (Fig. 1B). The calculation also revealed that Sn₂S₆⁴⁻ bound to a Na⁺ ion has a higher frequency Raman mode (186 cm⁻¹) compared to Sn₂S₆⁴⁻ bound to a Y³⁺ ion (163 cm⁻¹). Thus, the DFT results support that our experimental redshift in the Raman peak is consistent with the binding of Sn₂S₆⁴⁻ to the UCNP surface.

Successful Sn₂S₆⁴⁻ ligand exchange was also supported by zeta potential measurements that show a charge inversion from +30 mV after HBF₄ stripping to -40 mV upon Sn₂S₆⁴⁻ functionalization (Fig. 1C). Dynamic light scattering measurements showed an increase in the mean hydrodynamic radius from 16 nm to 68 nm, indicating some minor aggregation upon ligand exchange (Fig. S1, ESI†).

We then used electron microscopy to probe physical and compositional changes during the ligand exchange process (Fig. 2A and B). After carrying out a direct Sn₂S₆⁴⁻ exchange, we observe a decrease of about 2 nm in the average center-to-center distance of the UCNPs, confirming that the bulkier oleate has been replaced by more compact Sn₂S₆⁴⁻. EDS elemental mapping showed that sulfur and tin were uniformly dispersed among the UCNPs at both the nanoscale (Fig. 2C and Fig. S2, ESI†) and microscale (Fig. S3, ESI†). We also used the elemental mapping to estimate the Sn₂S₆⁴⁻ ligand coverage

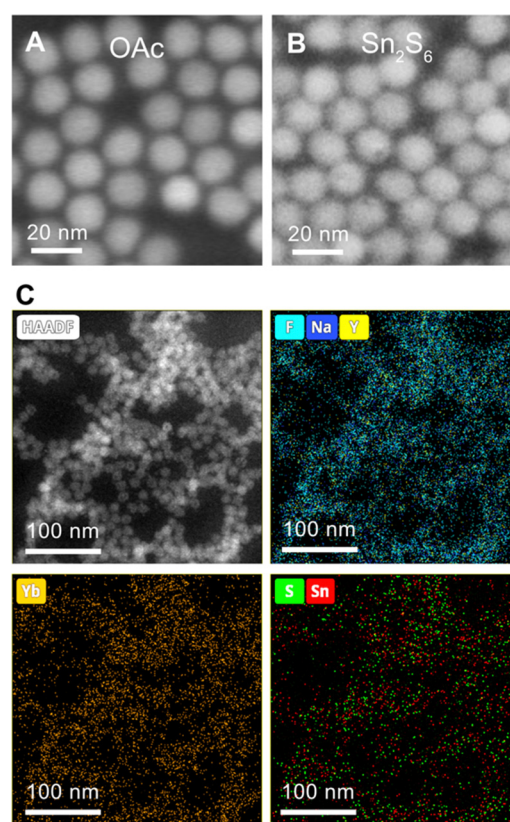


Fig. 2 Nanoscale characterization of 14-nm NaYF₄: 30% Yb³⁺, 0.5% Tm³⁺ UCNPs capped with Sn₂S₆⁴⁻ ligands. (A) and (B) Scanning transmission electron microscope images (STEM) of UCNPs capped with (A) oleate ligands or (B) Sn₂S₆⁴⁻ ligands via direct ligand exchange. The center-to-center distances are 18.3 ± 0.9 nm (oleate-capped) and 16.0 ± 1.1 nm (Sn₂S₆⁴⁻-capped). (C) High-angle annular dark-field imaging (HAADF) STEM and EDS elemental maps of Sn₂S₆⁴⁻-capped UCNPs obtained via indirect ligand exchange.

at 0.7 ligands per nm² (see discussion and Fig. S7 in the ESI† for details).

In summary, all analyses validate that NaYF₄ UCNPs can be effectively functionalized with Sn₂S₆⁴⁻ ligands through either

direct or indirect ligand exchange approaches. However, the indirect exchange gives a significantly higher yield and hence was our preferred method for subsequent experiments.

Enhancement of upconversion luminescence by $\text{Sn}_2\text{S}_6^{4-}$ ligands

We hypothesized that functionalizing UCNP with low-vibrational-energy $\text{Sn}_2\text{S}_6^{4-}$ would increase their UCL by reducing non-radiative relaxation pathways. To quantitatively assess the effect of $\text{Sn}_2\text{S}_6^{4-}$ ligands on the UCL, we measured the UCL from the same solution of ligand-stripped UCNP before and after titrating them with $\text{Sn}_2\text{S}_6^{4-}$ ligands, with overnight equilibration used to ensure complete exchange. We compared $\text{Sn}_2\text{S}_6^{4-}$ -capped UCNP with stripped UCNP (rather than with oleate-capped ligands) as this ensures consistency in the UCNPs concentration and type of solvent (NMF).

Upon functionalizing 8-nm-diameter NaYF_4 : 20% Gd^{3+} , 49% Yb^{3+} , 1% Tm^{3+} UCNP with $\text{Sn}_2\text{S}_6^{4-}$ ligands, we observed 5- to 16-fold enhancements in the UCL intensities of different radiative transitions of Tm^{3+} , compared to ligand-stripped UCNP capped with BF_4^- (Fig. 3A and B). In general, we find that higher energy (shorter wavelength) transitions have stronger enhancements, a trend consistent with previous studies using organic ligands.²⁰ One exception is the 450 nm emission, which has the lowest enhancement; we attribute this deviation from the trend to a small but non-negligible absorption from the $\text{Sn}_2\text{S}_6^{4-}$ ligands. We also observe increases in the UCL of 15-nm NaYF_4 : 40% Yb^{3+} , 60% Er^{3+} , with enhancement factors of 9–10 for the green and red emission lines (Fig. 3C and D). Kinetic time series measurements show that the enhancement factor rapidly increases within the first 4 minutes after $\text{Sn}_2\text{S}_6^{4-}$

coordination and reaches saturation in about 80 minutes (Fig. S4, ESI†).

The UCL enhancement due to the reduction in vibrational relaxation is corroborated by the lengthening of luminescence decay lifetimes upon $\text{Sn}_2\text{S}_6^{4-}$ exchange. When directly excited with 980 nm pulses, $\text{Yb}^{3+}/\text{Tm}^{3+}$ -doped UCNP (Fig. 3E and F) exhibited a significant increase in the lifetime of the Yb^{3+} 1010 nm emission, from 34 μs to 105 μs , which is also longer than the emission lifetime of oleate-capped UCNP (16 μs). A significant but smaller increase in the lifetime is also observed for the Tm^{3+} 800 nm emission (980 nm excitation) upon $\text{Sn}_2\text{S}_6^{4-}$ exchange (154 μs) compared with that of ligand-stripped UCNP (110 μs) and oleate-capped UCNP (111 μs). This increase in lifetime is also observed for the 540 nm emission from $\text{Sn}_2\text{S}_6^{4-}$ -capped $\text{Yb}^{3+}/\text{Er}^{3+}$ UCNP (Fig. 3G), which had an intensity-weighted lifetime of 197 μs , compared to a lifetime of 25 μs for ligand-stripped UCNP and 44 μs for oleate-capped UCNP (see ESI† for details on lifetime measurements and averaging). We note that nearly all the UCNPs decay curves shown in our work (and other work) exhibit multiple decay components. Our prior work has demonstrated that UCNPs lifetimes are complicated to interpret due to the complex energy transfer networks among dopants;²⁶ hence, it is difficult to conclusively attribute specific components in a decay curve to a specific process.

To elucidate the mechanism behind this UCL enhancement, we measured the enhancement factors for UCNP with different physical and chemical parameters. We investigated how the ligand enhancement is affected by the presence of an inert shell. For 14-nm NaYF_4 : 30% Yb^{3+} , 0.5% Tm^{3+} cores, we measured enhancement factors of 3–5 upon ligand functionalization. Upon the growth of a 5-nm shell, the UCL of the UCNP is

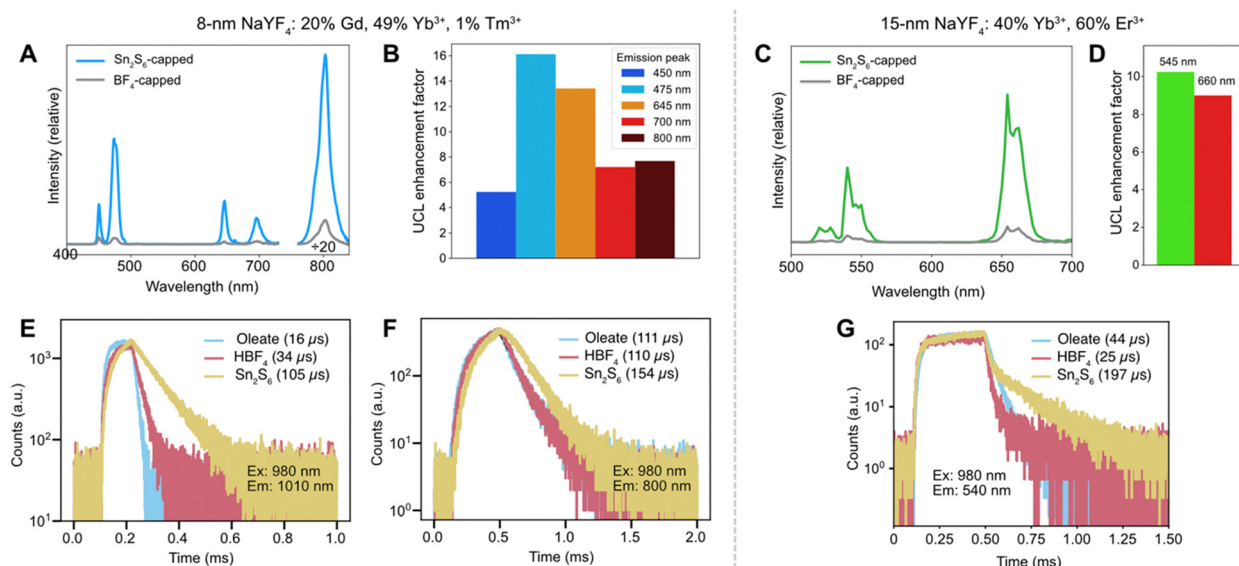


Fig. 3 Upconversion luminescence (UCL) of $\text{Sn}_2\text{S}_6^{4-}$ -capped UCNP. (A)–(D) UCL spectra and enhancement factors of $\text{Yb}^{3+}/\text{Tm}^{3+}$ -doped (A) and (B) and $\text{Yb}^{3+}/\text{Er}^{3+}$ -doped (C) and (D) UCNP before and after adding $\text{Sn}_2\text{S}_6^{4-}$ ligands. (E) and (F) Fluorescence lifetimes of the 1010 nm (E) or 800 nm (F) emissions from 8-nm NaYF_4 : 20% Gd^{3+} , 49% Yb^{3+} , 1% Tm^{3+} UCNP with different surface treatments using 980 nm excitation. (G) Fluorescence lifetimes of the 540 nm emission 6-nm NaYF_4 : 20% Gd^{3+} , 20% Yb^{3+} , 2% Er^{3+} UCNP with different surface treatments using 980 nm excitation.

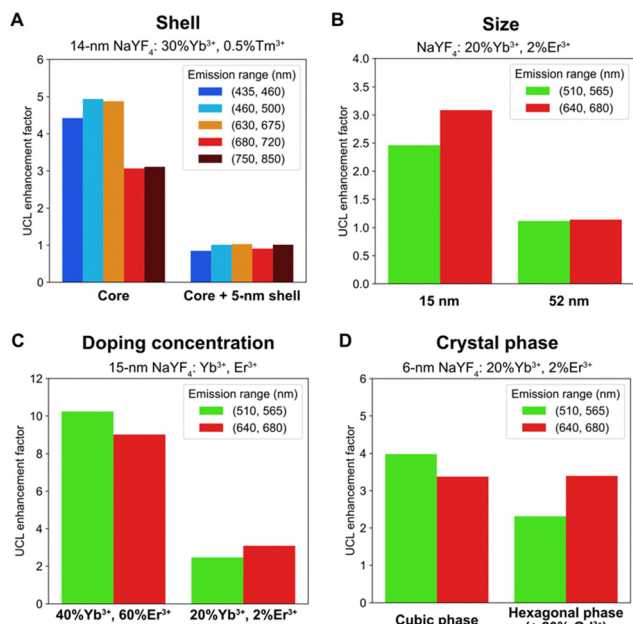


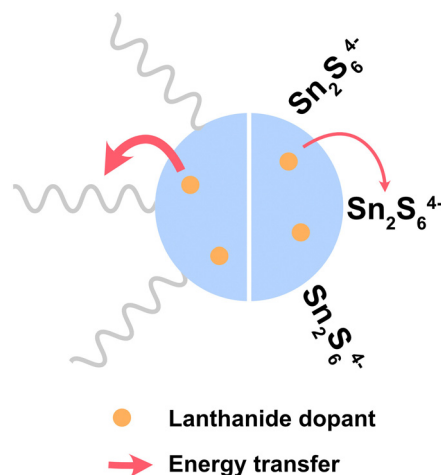
Fig. 4 Effect of UCNP parameters on the UCL enhancements by Sn₂S₆^{4−} ligands. Changes in the UCL enhancement factors upon growing an inert shell (A), or upon changing the doping concentration (B), size (C), or crystal phase (D). In all cases, the concentration of the Na₄Sn₂S₆ ligands was kept constant at 0.5 mM.

significantly enhanced compared to the UCNP cores, an effect that is well established. However, subsequent functionalization of the core–shell UCNP by Sn₂S₆^{4−} ligands does not result in further UCL enhancement (Fig. 4A). This implies that the Sn₂S₆^{4−} enhancement only occurs when ligands are in relatively close proximity to the photo-active dopant ions. We thus conclude that Sn₂S₆^{4−} molecules enhance UCL by reducing the available ligand vibrational modes that are coupled to excited dopant ions (Scheme 2).

Additionally, we found much smaller UCL enhancements for larger 52-nm UCNP compared to smaller 15-nm UCNP (Fig. 4B). The reduced enhancement is likely due to the smaller surface-to-volume ratios of larger UCNP, which are well known to be less susceptible to surface quenching.²⁷ We also found that UCNP with higher doping concentrations (40% Yb³⁺, 60% Er³⁺) had higher enhancement factors (9–10), while UCNP with lower doping concentrations (20% Yb³⁺, 2% Er³⁺, with similar sizes) have smaller enhancement factors (~2) (Fig. 4C). Finally, we found comparable enhancements for both cubic- and hexagonal-phase UCNP (Fig. 4D), revealing a negligible effect of the crystal structure on UCL enhancement.

Fabrication of a UCNP–SnS₂ nanocomposite

Sn₂S₆^{4−} complexes have been previously shown to transform into a semiconducting SnS₂ matrix upon annealing at relatively modest temperatures (<200 °C).²⁸ This property has led to the exploration of Sn₂S₆^{4−} as a promising ligand for integrating colloidal nanomaterials in electronic or optoelectronic devices. For instance, annealing Sn₂S₆^{4−}-capped QDs resulted in a



Scheme 2 Proposed mechanism of UCL enhancement by Sn₂S₆^{4−} ligands.

QD–SnS₂ composite that had high charge carrier mobilities and could be used as the active component in transistors.²¹ Here, we explore the fabrication of a UCNP–SnS₂ nanocomposite and evaluate its potential as an upconversion-based photo-detector.

Annealing of the Na₄Sn₂S₆ ligand without UCNP resulted in a film with a characteristic SnS₂ Raman peak at 314 cm^{−1} (Fig. 5A, green line). Upon annealing the Sn₂S₆^{4−}-capped UCNP at 350 °C to form the UCNP–SnS₂ composite, we observed the disappearance of the 182 cm^{−1} peak and the weakening of the 360 cm^{−1} peak, consistent with the decomposition of Sn₂S₆^{4−} (Fig. 5A, blue line). The identification of the SnS₂ peak for the UCNP–SnS₂ is more challenging due to interfering NaYF₄ peaks.

Scanning electron microscopy further supports the formation of a UCNP–SnS₂ composite. The composite with 9-nm UCNP (Fig. 5B) exhibits interconnected nanoscale nodules, significantly different than the original Sn₂S₆^{4−}-capped UCNP, which were clearly separated (Fig. 2B). These nodules are attributed to the formation of a SnS₂ matrix made from the decomposition and fusing of the Sn₂S₆^{4−} ligands. An alternative hypothesis is that these nodules are from the sintering and grain growth of the NaYF₄ UCNP themselves. However, this hypothesis can be rejected since powder X-ray diffraction peaks do not significantly narrow following annealing (Fig. 5C), indicate no significant increase in the size of the NaYF₄ domains. Additional characterization (e.g., X-ray photoelectron spectroscopy) could potentially be used to further confirm the formation of the NaYF₄/SnS₂ composite.

Our analyses thus support the formation of nanoscale upconverting emitters embedded in a semiconducting matrix. This composite allows the desirable optical properties of UCNP to be retained while adding the important capability to electronically interface with each UCNP through the semiconducting matrix. Further work could include more detailed studies on how the annealing and formation of the UCNP–SnS₂ composites affect UCL properties (e.g., intensity, linewidth, peak positions).

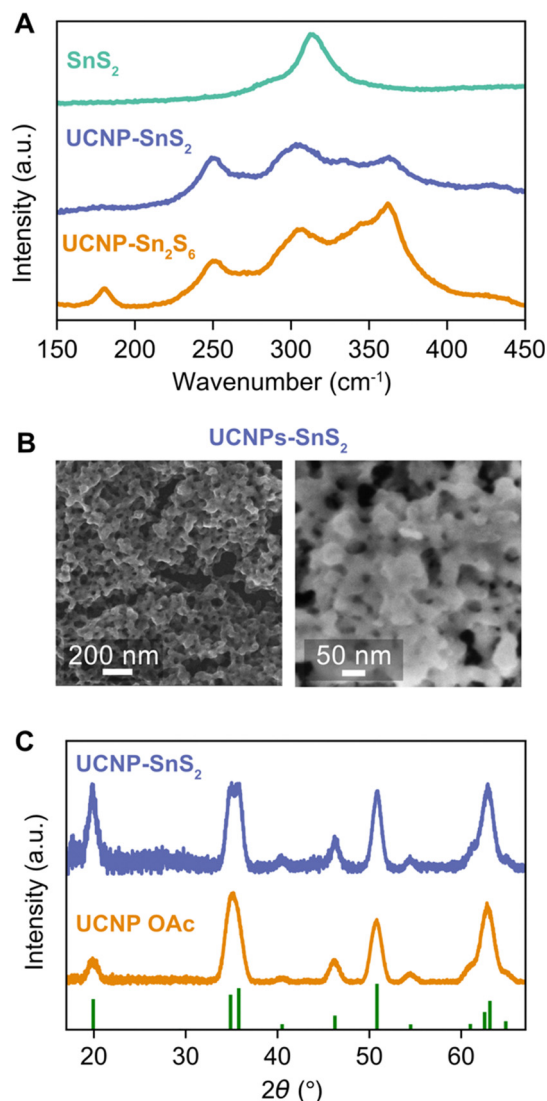


Fig. 5 Annealing Sn₂S₆⁴⁻-capped 9-nm NaYF₄: 8% Tm³⁺ UCNP at 350 °C to form a UCNP-SnS₂ nanocomposite. (A) Raman spectra of the Sn₂S₆⁴⁻-capped UCNP before (orange line) and after (blue line) annealing. Also shown is the spectrum of the SnS₂ matrix formed by annealing Na₄Sn₂S₆ (green line). (B) SEM images of the UCNP embedded in the SnS₂ matrix. (C) X-ray diffraction spectra of the UCNP-SnS₂ nanocomposite (blue line) and oleate-capped UCNP (orange line). The reference spectrum for hexagonal-phase NaYF₄ (PDF# 04-022-5333) is also shown (green line).

UV and NIR photoconductivity of the UCNP-SnS₂ nanocomposite

One benefit of encapsulating UCNP in a continuous semiconductor matrix is that it allows for easier integration of UCNP into electronic devices. While the dielectric UCNP and their ligands are insulating, UCNP/semiconductor composites could in principle provide a pathway to new solution-processable optoelectronic devices that incorporate UCNP.

To demonstrate the capabilities of the UCNP-SnS₂ nanocomposite, we evaluated its use as a photodetector (Fig. 6A). To fabricate a simple proof-of-concept device, we drop-cast

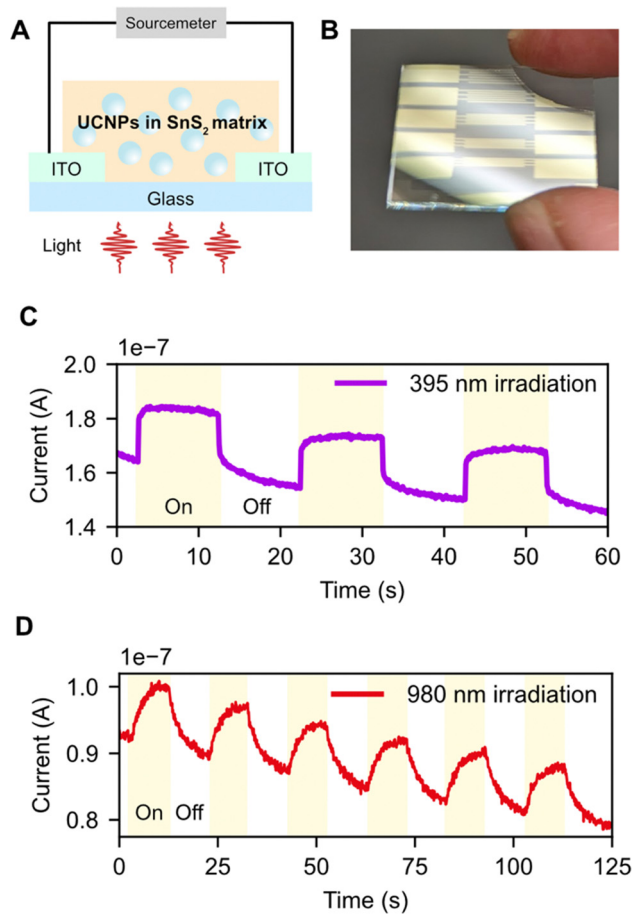
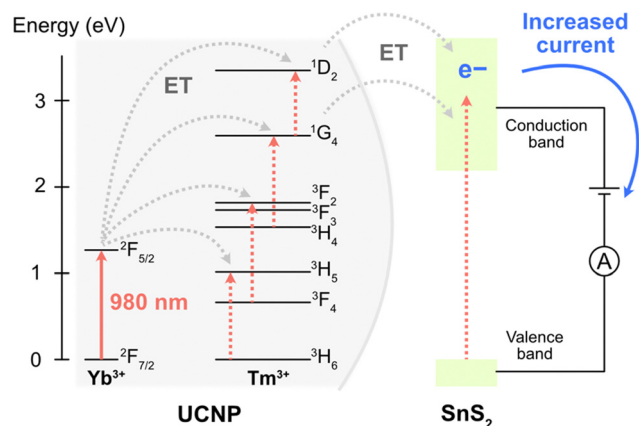


Fig. 6 Photoconductivity of a UCNP-SnS₂ nanocomposite film. (A) Device schematic of the photoconductor. (B) Picture of the interdigitated indium tin oxide (ITO) electrodes. (C) and (D) Photoconductivity time curves of a film of 24-nm NaYF₄: 30% Yb³⁺, 0.5% Tm³⁺/NaYF₄ UCNP (14 nm core/5 nm shell) in a SnS₂ matrix upon 395 nm (C) or 980 nm (D) irradiation.

Sn₂S₆⁴⁻-capped UCNP onto interdigitated ITO electrodes on glass that was obtained commercially (Fig. 6B) and annealed the sample at 350 °C to form the UCNP-SnS₂ composite. We hypothesized that the embedded UCNP would absorb IR light and emit upconverted UV and blue light that could be absorbed by the surrounding SnS₂ matrix (Scheme 3). The resulting increase in the concentration of charge carriers in the SnS₂ semiconductor in principle should lead to an increase in the observed current at a constant applied voltage.

As a first step, we confirmed that our photoconductor could detect UV light that is absorbed directly by the SnS₂ matrix. Indeed, we observed a clear increase in the current when 395 nm light ($\sim 60 \text{ mW cm}^{-2}$) was incident on the substrate (Fig. 6C). Next, we substituted the 395 nm light for a 980 nm laser light source ($\sim 300 \text{ mW cm}^{-2}$) and successfully detected an increase in current upon irradiation (Fig. 6D). Since ITO and SnS₂ have negligible absorption at 980 nm, the photocurrent is attributed to absorption by the UCNP followed by upconversion and transfer of energy to the SnS₂ matrix. While the photocurrent was weaker than that induced by 395 nm light,



Scheme 3 Proposed mechanism of photodetection by the UCNP–SnS₂ nanocomposite. (ET: energy transfer.)

the response can be improved by increasing the film thickness and quality, optimizing the UCNP loading percent, and engineering a better overlap between the emission of the UCNP and absorption of the semiconducting matrix. This proof-of-concept device demonstrates a viable path for using semiconducting ligands and matrices to electronically interface with UCNPs within an optoelectronic device, circumventing the physical and processing challenges associated with simply mixing UCNPs with SnS₂ powder.

For all our devices, we also consistently observed a decrease in the background current as a function of time after application of the voltage. When the voltage was stopped and restarted, the current level was reset to its original value. This implies that this decrease in current is due to capacitance, which we attribute to misalignment between the energy levels of ITO and our active materials. Further optimization of the contact material should reduce or remove this effect.

Conclusions

In this study, we investigated the surface functionalization of lanthanide-doped UCNPs with Sn₂S₆^{4−} inorganic metal complexes and verified the ligand exchange *via* Raman spectroscopy and EDS elemental mapping. We found that the Sn₂S₆^{4−} ligands can enhance the UCL intensity of both Yb³⁺/Tm³⁺- and Yb³⁺/Er³⁺-doped UCNPs, with enhancement factors up to 16 for small, highly doped UCNPs. Upon annealing, these Sn₂S₆^{4−}-capped UCNPs can also be transformed into a nanocomposite of UCNPs embedded within a matrix of semiconducting SnS₂. This nanocomposite can be used to harness the nonlinear optical properties of UCNPs in charge-based devices such as photodetectors. To demonstrate this, we tested a proof-of-concept UCNP–SnS₂ device that displays photoconductive behavior under both UV and NIR light. We have also demonstrated in preliminary work that Sn₂S₆^{4−}-functionalization can be extended to photon avalanching nanoparticles with no significant changes to their nonlinear responses (see ESI† and Fig. S5 for details).^{6,29,30}

Our findings show how semiconducting inorganic complexes with low vibrational energies can be used to enhance the optical properties of UCNPs while seamlessly facilitating the fabrication of a low-phonon-energy matrix that allows UCNPs to be accessed electronically. With further optimization, this approach should be extensible to other UCNP host materials and other nanoscale emitters that can benefit from a non-epitaxial, low-vibrational-energy environment.

Methods

Na₄Sn₂S₆·14H₂O synthesis

The synthesis of Na₄Sn₂S₆·14H₂O was carried out according to previous reports.^{24,31} To a 100 mL glass bottle, Na₂S·9H₂O (14.4 g, 60 mmol) and 90 mL DI H₂O were added and stirred for 5 h to form a clear solution. To a 50 mL centrifuge tube, SnCl₄·5H₂O (7.0 g, 20 mmol) and 5 mL DI H₂O were added and stirred for 5 h to form a clear solution. The SnCl₄ solution was then added dropwise (using a separatory funnel) into the Na₂S solution while stirring. The resulting crude Na₄Sn₂S₆ solution was then stirred overnight. The crude solution was then added dropwise to 300 mL acetone in a 500 mL glass bottle under vigorous stirring. A yellowish-white precipitate is formed during this process. After the addition, the suspension is placed in the freezer for 5 h. At the same time, 100 mL of neat acetone in a separate glass bottle is also chilled in the freezer for 5 h. At this point, the chilled suspension is decanted and the solid is shaken together with 100 mL of chilled acetone. The suspension is decanted again and the solid is dried in a vacuum oven at room temperature overnight to give an off-white pale precipitate (5.53 g, 72% yield).

Na₄Sn₂S₆ ligand exchange of oleate-capped NaYF₄ UCNPs

Exchange with intermediate ligand stripping. To 100 μL of UCNPs (~100 mg mL^{−1}), was added 1 mL of toluene. Then, 25 μL of 0.5 M HBF₄ in DMF was added to the solution, which immediately resulted in the formation of a precipitate. [To make a 0.5 M HBF₄ stock solution, HBF₄-diethyl ether solution (343 μL, 2.5 mmol) was slowly added to DMF (4.66 mL). Caution: exothermic reaction.] The suspension was sonicated for 5 min followed by centrifugation (5000 rpm, 2021g, 1 min). The UCNPs were then washed twice with 0.3 mL DMF/0.7 mL toluene and redispersed in 2 mL of DMF. To this solution was added 50 mM Na₄Sn₂S₆ solution in NMF (20–200 μL) to achieve a Na₄Sn₂S₆ ligand concentration of 0.5–5 mmol. The solution was left to sit overnight, centrifuged (5000 rpm, 2021g, 1 min), and redispersed in NMF or DMF with sonication.

Direct exchange (low yield). To 200 μL of UCNPs (~100 mg mL^{−1}), was added 1 mL of ethanol followed by centrifugation (3000 rpm, 728g, 30 s). NMF (1 mL) was added followed by vortexing to get a suspension. To the suspension, 20 μL of 50 mM Na₄Sn₂S₆ solution in NMF was added followed by vortexing and then sonication for 1 h. The suspension was centrifuged (5000 rpm, 2021g, 30 s) to remove unreacted UCNPs. To the supernatant, acetonitrile (2 mL) was added

followed by centrifugation (10 000 rpm, 8084g, 1 min). The residue was redissolved in 100 μ L NMF, to which was added 400 μ L acetonitrile. The suspension was centrifuged (10 000 rpm, 8084g, 1 min) and finally redissolved in 100 μ L NMF.

Formation of UCNP-SnS₂ composite by annealing Sn₂S₆⁴⁻-capped UCNPs. Sn₂S₆⁴⁻-capped UCNPs were deposited on a Si wafer or glass slide followed by annealing on a hot plate at 350 °C for approximately 15 min.

Data availability

Data will be made available upon request by contacting the authors.

Conflicts of interest

There are no conflicts of interest to declare.

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