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UV-Vis-NIR luminescence properties and energy transfer mechanism of LiSrPO₄:Eu²⁺, Pr³⁺ suitable for solar spectral converter

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Abstract: An efficient near-infrared (NIR) phosphor LiSrPO₄:Eu²⁺, Pr³⁺ is synthesized by solid-state reaction and systematically investigated using x-ray diffraction, diffuse reflection spectrum, photoluminescence spectra at room temperature and 3 K, and the decay curves. The UV-Vis-NIR energy transfer mechanism is proposed based on these results. The results demonstrate Eu²⁺ can be an efficient sensitizer for harvesting UV photon and greatly enhancing the NIR emission of Pr³⁺ between 960 and 1060 nm through efficient energy feeding by allowed 4f-5d absorption of Eu²⁺ with high oscillator strength. Eu²⁺/Pr³⁺ may be an efficient donor-acceptor pair as solar spectral converter for Si solar cells.

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References and links

1. Introduction

Nowadays, solar cells are attracting significant attention as a means to generate clean and green energy because of the energy and environmental crisis. The most widely used solar cells are based on crystalline silicon (c-Si). Si solar cells most effectively convert near infrared (NIR) photons of energy close to the semiconductor band gap (Eg≈1.12eV, λ≈1000 nm). However, the incident solar spectrum is dominant in the UV-Vis region. The mismatch between the incident solar spectrum and the spectral response of Si solar cells leads to charge thermalization in the process of photovoltaic (PV) conversion and is responsible for about 70% energy loss in the form of heat. It is one of the main reasons that limit the cell efficiency [1, 2]. If UV-Vis photons of higher energy can be converted to NIR photons of lower energy prior to being absorbed by the Si solar cells, the charge thermalization of Si solar cell will be greatly reduced due to better energy matching between the incident NIR lights and the spectral response of the Si solar cells.

Downshift (DS) is such an important method to modify the solar spectrum. Recently, K. R. McIntosh and co-authors demonstrated that the external quantum efficiency of a Si solar cell increases to up to 40% by encapsulating a layer of DS molecules into the PV device [3]. The DS molecules they used are fluorescent organic dyes. They have broad absorption bands and high luminescence quantum efficiency, but exhibit a relatively poor chemical stability, significant re-absorption and an emitted light in the visible region (λ<750 nm) that still does not match the maximum spectral response (λ≈1000 nm) of the Si solar cells [4,5]. Therefore, luminescent DS materials possessing excellent chemical stability, strong and broad absorption in visible region, intense NIR emission peaking at ~1000 nm and high quantum efficiency are in great need.

Rare earth luminescent inorganic materials are expected to be an alternative to organic dyes. Recently, much effort has been made to develop phosphors activated by Nd3+ [6], Eu3+ [7], Yb3+ [8], Ce3+-Tb3+ [9] or Dy3+-Yb3+ [10]. However, they have no absorptions or weak f-f absorptions in the UV (300-380 nm) and consequently lead to weak NIR emission. These drawbacks limits them potential application in Si solar cell.

Comparatively, Pr3+ ion has a rich energy-level structure, allowing for direct absorption of visible photons, for instance, the 3H4→1D2 (~600 nm), 1Pj (J = 0, 1, 2), 1I6 (440-490 nm) transitions, and allowing for the NIR emission at ~1000 nm from the 1G4→3H4 transitions, which matches the optimal spectral response of the Si solar cells. Furthermore, Pr is relatively abundant and inexpensive compared to Yb. These motivations prompted us to explore novel luminescent DS materials activated by Pr3+ ions for Si solar cell applications. In this paper, we have developed a novel NIR phosphor LiSrPO4:Eu2+,Pr3+ (LSP: Eu2+,Pr3+), which shows promise as a solar spectral converter for Si solar cells. It has excellent chemical stability. More importantly, it can harvest UV-Vis photons and exhibit an intense NIR emission of Pr3+ at ~1000 nm. We demonstrate that Eu2+/Pr3+ ions may be an efficient donor-acceptor pair as solar spectral converter for Si solar cells, and Eu2+ ions can be an efficient sensitizer for harvesting UV photon and greatly enhancing the NIR emission of Pr3+ ions through efficient energy feeding by allowed 4f-5d absorption of Eu2+ ions with high oscillator strength.
2. Experiment

Eu$^{2+}$ or Pr$^{3+}$ singly doped and Eu$^{2+}$-Pr$^{3+}$ co-activated LSP phosphors were prepared by a conventional solid-state reaction technique. The starting materials, LiH$_2$PO$_4$ (97%), SrCO$_3$ (A.R.), NH$_4$H$_2$PO$_4$ (A.R.), Eu$_2$O$_3$ (99.99%) and Pr$_6$O$_{11}$ (99.99%) were weighed in stoichiometric amounts. Subsequently the powder mixture was thoroughly mixed in an agate mortar by grinding and was transferred into crucibles. Finally, they were pre-calcined at 600°C for 3 h in air and sintered at 1300°C for 3 h under N$_2$/H$_2$ atmosphere. Ca$_2$BO$_3$Cl:Ce$^{3+}$, Tb$^{3+}$, Yb$^{3+}$ (CBC) was also prepared by a conventional solid-state reaction method according to [11].

The phase purity of the prepared phosphors was investigated by a Rigaku D/max-IIIA X-ray diffractometer (XRD) with Cu K$_\alpha$ radiation ($\lambda = 1.5406\,\text{Å}$) at 40kV and 30mA. The XRD patterns were collected in range of $10^\circ \leq 2\theta \leq 70^\circ$.

The photoluminescence (PL) and photoluminescence excitation (PLE) spectra at room temperature and 3K as well as the decay curves were measured by FSP920 Time Resolved and Steady State Fluorescence Spectrometers (Edinburgh Instruments) equipped with a 450W Xe lamp, a 150w nF900 flash lamp, a 100w mF920H lamp, TM300 excitation monochromator and double TM300 emission monochromators, Red sensitive PMT and R5509-72 NIR-PMT in a liquid nitrogen cooled housing (Hamamatsu Photonics K.K). The spectral resolution for the steady measurements is about 0.05 nm in UV-VIS and about 0.075–0.01 nm in NIR, the experimental conditions for the transient measurements of the Eu$^{2+}$ ions are a pulse width of 1.0–1.6ns, a repetition rate of 40kHz and the lifetime range of 100ps–50µs and the Pr$^{3+}$ ions are a pulse width of 1–2µs, a repetition rate of 50Hz and the lifetime range of 100µs–200s. For PL and PLE measurements at 3K, the sample was mounted in a Optistat AC-V12 actively cooled optical cryostat, based on 0.25W @ 4K PTR (pulse tube refrigerator), with a ITC503 temperature controller and a water cooled compressor.

The powder diffuse reflection spectra (DRS) of these samples were measured on a Cary 5000 UV-Vis-NIR spectrophotometer (Varian) equipped with double out-of-plane Littrow monochromator, using polyfluortetraethylene as a standard reference in the measurements.

3. Results and discussion

3.1 Phase characterization

![Fig. 1. Powder XRD pattern of LSP: Eu$^{2+}_{0.005}$, Pr$^{3+}_{0.0011}$.](image)

Figure 1 shows the powder XRD pattern of LSP: Eu$^{2+}_{0.005}$, Pr$^{3+}_{0.0011}$, which was indexed using the software of Powder X. The Fig. of merit (F$_{\text{M}}$) is evaluated to be 69.06 [12]. The doped product crystallizes as hexagonal LiSrPO$_4$ phase with a space group of P6$_3$, and a set of lattice
parameters are $a = b = 4.996(2)$ Å, $c = 8.209(4)$ Å, $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$. It can be seen that most of the observed peaks satisfy the reflection condition except for some weak peaks due to minor unknown impurities. The powder XRD pattern also matches well with the reference data [13–15]. These indicate the dopants have no obvious influence on the crystalline structure of the host.

3.2 Luminescence properties of LSP: Pr$^{3+}$

Fig. 2. PLE (a: $\lambda_{\text{em}} = 618$ nm) and PL (b: solid, $\lambda_{\text{ex}} = 443$ nm; dash, $\lambda_{\text{ex}} = 581$ nm) spectra of LSP: Pr$^{3+}$0.0045 at 3 K and the luminescence decay curves (c: $\lambda_{\text{ex}} = 484$ and 581 nm, d: $\lambda_{\text{em}} = 609$ nm) of LSP: Pr$^{3+}$0.0045 at room temperature.

Figures 2(a) and 2(b) show the PLE and PL spectra of LSP: Pr$^{3+}$0.0045 at 3 K. Such a lower temperature was used in order to minimize the effects of the host vibration, or phonons, on the optical properties of Pr$^{3+}$ ions. Monitoring the emission at 618 nm, a series of excitation peaks at 444 nm and 447 nm, 468 nm and 473 nm, 484 nm, and 590 nm are due to the absorption transitions of $^3H_4 \rightarrow ^3P_2$, $^3H_4 \rightarrow ^3P_1$ and $^1I_6$, $^3H_4 \rightarrow ^3P_0$, and $^3H_4 \rightarrow ^1D_2$ of the Pr$^{3+}$ ions, respectively. Under excitation into the $^3P_2$ and $^1D_2$ levels, respectively, Pr$^{3+}$ ion exhibits distinct emission features. The PL spectrum ($\lambda_{\text{ex}} = 581$ nm) only consists of several emission peaks in the wavelength range of 590-630 nm, due to the transitions from $^1D_2$ to the Stark levels of $^3H_4$. Whereas the PL spectrum ($\lambda_{\text{ex}} = 443$ nm) presents not only weak emission peaks at 482 nm, 640 and 724 nm, assigned to $^3P_0 \rightarrow ^3H_4$, $^3P_0 \rightarrow ^3F_{2,4}$, but also the dominant emission peaks in the wavelength range of 590-630 nm.

In general, the decay time of the emission from $^3P_0$ is 0.135-50 µs, greatly shorter than that from $^1D_2$, which is about 50-250 µs [16]. To further confirm the assignments to the emissions between 590 nm and 630 nm, the luminescence decay curves ($\lambda_{\text{ex}} = 484$ nm and 581 nm, $\lambda_{\text{em}} = 609$ nm) of LSP: Pr$^{3+}$0.0045 were measured and presented in Figs. 2(c) and 2(d). The results show that the decay curves are almost identical and the average decay time is about 105.3 µs and 106.5 µs when excited to $^3P_0$ and $^1D_2$ levels, respectively. Therefore, it is reasonable to assign the emissions between 590 nm and 630 nm to the $^1D_2$ levels.
It is interesting to note that not only the shapes but also the position of the emission peaks between 590 nm and 630 nm are exactly the same when excited into either $^3\text{P}_2$ or $^1\text{D}_2$ levels. Why can the radiative transitions from $^1\text{D}_2$ to $^3\text{H}_4$ be observed when excited into $^3\text{P}_2$ level (Fig. 3 (process 2a))? There are two possible ways as shown in Fig. 3 (process 2b and 2c). One is non-radiative relaxation process (2b) directly from $^3\text{P}_0$ to $^1\text{D}_2$ level assisted by phonons. The energy gap between $^3\text{P}_0$ and $^1\text{D}_2$ levels is about 3449 cm$^{-1}$. The maximum vibration frequency of phosphate is about 1037 cm$^{-1}$ [17]. That is to say at least three phonons are needed to bridge this energy gap. In general, if the energy gap is more than 5 times the energy of the highest energy phonon, phonons assisted non-radiative relaxation process from the upper level to the lower level is impossible. In the present case, it is therefore expected that multiphonon relaxation process from $^3\text{P}_0$ to $^1\text{D}_2$ level may occur but its possibility is relatively low. The other is cross-relaxation process (2c), $[^3\text{P}_0, ^3\text{H}_4] \rightarrow [^3\text{H}_6, ^1\text{D}_2]$. The energy gaps between $^3\text{P}_0$ and $^3\text{H}_6$ levels, and $^1\text{D}_2$ and $^3\text{H}_4$ levels are 16421 cm$^{-1}$ and 16622 cm$^{-1}$, respectively. The difference between them is only about 201 cm$^{-1}$. Therefore, the cross-relaxation $[^3\text{P}_0, ^3\text{H}_4] \rightarrow [^3\text{H}_6, ^1\text{D}_2]$ is considered to be relatively more efficient than multiphonon relaxation process directly from $^3\text{P}_0$ to $^1\text{D}_2$ levels. Through the cross-relaxation (2c), it is reasonable to observe the prominent red emissions from the $^1\text{D}_2$ level as well as the $^3\text{P}_0$ level upon being pumped into the $^3\text{P}_2$ level ($\lambda_{\text{ex}} = 443$ nm) as shown in Fig. 2. In summary, the whole blue-to-red ET process could be expressed as (2a→2c→606 nm) for the prominent red emissions from the $^1\text{D}_2$ level.

As shown in Fig. 3, the energy gaps between $^1\text{G}_4$ and $^1\text{D}_3$, and $^3\text{H}_4$ and $^3\text{F}_4$ are 6622 cm$^{-1}$ and 6163 cm$^{-1}$, respectively. The difference is only about 459 cm$^{-1}$. Therefore, it is theoretically expected that the cross-relaxation (2d), $[^1\text{D}_3, ^3\text{H}_4] \rightarrow [^1\text{G}_4, ^3\text{F}_4]$ occurs. That is to say the $^1\text{G}_4$ level can be populated via two steps of cross-relaxation (2c and 2d) when excited into $^3\text{P}_0$ levels. Consequently, the NIR emissions from the $^1\text{G}_4$ level are expected. Figure 4a presents the emission spectra of LSP: Pr$^{3+}$ in 0.0045 in NIR region at 3 K. Under 484 nm ($^3\text{P}_0$) and 590 nm ($^1\text{D}_2$) excitation, Pr$^{3+}$ ion shows almost the same NIR emission except the emission intensity. The sharp NIR1 emissions at 1042 nm, 1053 nm and 1064 nm are due to the transitions from the excited $^1\text{G}_4$ level to the different Stark levels of the ground $^3\text{H}_4$ level. These results further prove that the cross-relaxation (2d), $[^1\text{D}_3, ^3\text{H}_4] \rightarrow [^1\text{G}_4, ^3\text{F}_4]$, is efficient.
in LSP. Additionally, there are some other sharp emissions between 950 and 1040 nm. The NIR2 emissions at 969 nm, 978 nm, 982 nm and 989 nm, and the other NIR3 emissions at 1007 nm, 1017 nm and 1025 nm, 1028 nm and 1035 nm are attributed to the transitions from the excited $^1D_2$ level to the different Stark levels of $^3F_3$ and $^3F_4$, respectively. In summary, the whole blue-to-NIR ET process could be expressed as $(2d \rightarrow 2c \subset \overrightarrow{2d \rightarrow \text{NIR}})$ for the prominent NIR emissions from the $^1G_4$ and $^1D_2$ levels.

![Fig. 4. (a): The PL spectrum of LSP: Pr$^{3+}$0.0045 in near-infrared region ($\lambda_{ex} = 484\text{nm and 590nm}$) at 3K; The diffuse reflection spectrum (b), PLE spectra (c, $\lambda_{em} = 1035\text{nm}$) of LSP: Pr$^{3+}$0.0045 at room temperature.](image)

Recently, Andries Meijerink and his co-authors reported near-infrared quantum cutting of SrF$_2$:Pr$^{3+}$ for photovoltaics [18]. In order to prove the existence of quantum cutting, they compared the diffuse reflection and excitation spectra and found the ratio of the total area of the peaks due to the $^3H_4 \rightarrow ^3P_J$ and $^3H_4 \rightarrow ^1I_6$, transitions relative to that of the $^3H_4 \rightarrow ^1D_2$ peak in the excitation spectrum should be twice as large as the ratio similarly obtained in the diffuse reflectance spectra. In our case, the diffuse reflection (absorption) in the region of $^3H_4 \rightarrow ^3P_{0,1,2}$ and $^1I_6$ transitions (430-488 nm) and $^3H_4 \rightarrow ^1D_2$ transitions (575-610 nm) were also recorded and compared with the excitation spectra of NIR emission as shown in Fig. 4 b and c in order to further study the mechanism of NIR emission of Pr$^{3+}$ in LSP. The ratio of the total absorption (integrated spectral area) of the $^3H_4 \rightarrow ^3P_J$ and $^3H_4 \rightarrow ^1I_6$ transitions relative to that of the $^3H_4 \rightarrow ^1D_2$ transition was determined to be 4.88. From the PLE of LSP: Pr$^{3+}$0.0045, the ratio for the same transition is 4.91. Within experimental uncertainty, this ratio is equal to the value of that of the absorption strengths (from diffuse reflectance), confirming that for every photon absorbed into the $^3P_J$ and $^1I_6$ levels, only one NIR photon was generated. Therefore, the blue-to-NIR quantum cutting process from the $^3P_0$ level does not occur in LSP.
3.3 Luminescence properties of LSP: Eu$^{2+}$$_{y}$, Pr$^{3+}$$_{y}$

As shown in Fig. 5(a), the PLE and PL spectra of LSP: Eu$^{2+}$ contains a broad absorption band at 250-425 nm and a blue emission band at 445 nm, attributed to 4f-5d allowed transition of Eu$^{2+}$ ions in the LSP host [13]. Figure 5(b) presents the PLE and PL spectra of LSP: Pr$^{3+}$. The assignments of absorption and emission transitions of Pr$^{3+}$ at room temperature are the same to that of Pr$^{3+}$ at 3 K (as shown in Figs. 2(a) and 2(b)). Figure 5(c) gives the PLE and PL spectra of LSP: Eu$^{2+}$, Pr$^{3+}$. Monitoring the emission at 609 nm, the PLE spectrum of LSP: Eu$^{2+}$, Pr$^{3+}$ contain two absorption bands: broad band of Eu$^{2+}$ and sharp peaks of Pr$^{3+}$. Under 350 nm excitation, blue emission of Eu$^{2+}$ is prominent at 445 nm and weak sharp peaks of Pr$^{3+}$ is situated between 550 and 650 nm, which is magnified and clearly shown in the inset of Fig. 5(c). The appearance of 4f$\rightarrow$5d transitions of Eu$^{2+}$ ions in the PLE spectrum of Pr$^{3+}$ and the existence of the $^1D_2\rightarrow^3H_4$ transitions of Pr$^{3+}$ ion in the PL spectrum of Eu$^{2+}$ in LSP:Eu$^{2+}_{0.005}$, Pr$^{3+}_{0.0045}$ suggest that UV-to-red ET from Eu$^{2+}$ to Pr$^{3+}$ occurs.

Figures 6(a), 6(b), and 6(c) present the dependence of the intensity of the visible and NIR emission on the concentration ($y$) of Pr$^{3+}$ ions in LSP: Eu$^{2+}_{0.005}$, Pr$^{3+}_y$. It is clearly seen that, as the Pr$^{3+}$ ion concentration increases from 0 mol% to 5.6 mol%, the blue emission intensity of Eu$^{2+}$ ion decreases greatly whereas both red and NIR emission intensities of Pr$^{3+}$ ion reach a maximum at 4.5 mol% Pr$^{3+}$ and then decrease due to concentration quenching. Furthermore, it is seen that NIR emission of Pr$^{3+}$ increases more significantly than red emission of Pr$^{3+}$, strongly supporting that the cross-relaxation (Fig. 3, process 2d), $[^1D_2, ^3H_4] \rightarrow [^1G_4, ^3F_4]$, is efficient in LSP as discussed above.

The inset of Fig. 6(b) presents PL spectrum of LSP: Eu$^{2+}_{0.005}$, Pr$^{3+}_{0.0045}$ (LSP) and Ca$_2$BO$_2$Cl:Ce$^{3+}_{0.002}$, Tb$^{3+}_{0.01}$, Yb$^{3+}_{0.01}$ (CBC). It was reported that Ca$_2$BO$_2$Cl:Ce$^{3+}$, Tb$^{3+}$, Yb$^{3+}$ was promising as a NIR emitting phosphor for use in solar spectral conversion [11]. It demonstrates that Ce$^{3+}$ ion is an efficient sensitizer harvesting UV photon and greatly enhancing the NIR emission of Yb$^{3+}$ ion through efficient energy feeding by allowed 4f-5d absorption of Ce$^{3+}$ ion with high oscillator strength. Comparatively, LSP: Eu$^{2+}_{0.005}$, Pr$^{3+}_{0.0045}$ exhibits NIR emission 6 times as intense as that of CBC on 4f-5d excitation of Ce$^{3+}$. These results demonstrate that LSP: Eu$^{2+}$, Pr$^{3+}$ can harvest UV-Vis photons of the incident solar spectrum and emit intense NIR emission. It may be a potential luminescent DS material to increase the efficiency of the solar spectral convertor.
In order to provide convincing evidence for the existence of ET from Eu$^{2+}$ to Pr$^{3+}$ and estimate its efficiency, the decay curves were recorded and the data were presented in the inset of Fig. 6(d). It is obvious that with increasing amount of Pr$^{3+}$, the lifetime of Eu$^{2+}$ ions gradually decreases. In the absence of Pr$^{3+}$, the lifetime of Eu$^{2+}$ ion is 0.77 μs. When the amount of codoped Pr$^{3+}$ is up to 5.6 mol %, the lifetime of Eu$^{2+}$ ion is 0.33 μs. Such behavior further indicates that the energy of these excited Eu$^{2+}$ ions is transferred to Pr$^{3+}$ ions. Furthermore, the ET efficiency ($\eta_{ET}$) from Eu$^{2+}$ to Pr$^{3+}$ was evaluated based on the following expression [19].

$$\eta_{ET} = 1 - \frac{\tau_x}{\tau_0}$$

where $\tau_0$ and $\tau_x$ stand for the lifetimes of Eu$^{2+}$ in the absence and presence of Pr$^{3+}$, respectively. The ET efficiency increases gradually with the concentration of Pr$^{3+}$. The maximum value of $\eta_{ET}$ is estimated to be 56.8% with 5.6 mol % Pr$^{3+}$. Such a relatively high value of $\eta_{ET}$ does not seem to be consistent with the very weak red emission of Pr$^{3+}$ as shown in Fig. 6d. But if one keeps in mind that the cross-relaxation (Fig. 3, process 2d), [$D_2$, $J_4$] $\rightarrow$ [$G_4$, $F_4$], is efficient in LSP, it is reasonable to observe weak red emission of Pr$^{3+}$ since most of the red emissions are converted to the NIR emission of Pr$^{3+}$ ion.

We have successfully demonstrated that Eu$^{2+}$ ion can be used as a donor utilizing UV photons and greatly enhancing the NIR emission of Pr$^{3+}$ ion through efficient energy feeding by allowed 4f-5d absorption of Eu$^{2+}$ ion with high oscillator strength. The detailed UV-to-NIR ET process can be described as follows (Fig. 3): first, Eu$^{2+}$ ion directly absorbs a UV photon via the allowed 4f→5d transitions (process 1a). Subsequently, the energy in the lowest 5d excited level (~22472 cm$^{-1}$) of Eu$^{2+}$ ion relaxes to the $^3P_1$ level (21142 cm$^{-1}$) of Pr$^{3+}$ ion via resonant ET (process 2a). From the $^3P_2$ level, the energy of the excited Pr$^{3+}$ ion relaxes into
the $^3P_0$, $^1D_2$ and $^1G_4$ levels by a two step cross-relaxation (process 2c and 2d), $[^1P_0, ^3H_4] \rightarrow [^3H_6, ^1D_2]$ and $[^1D_2, ^3H_4] \rightarrow [^1G_4, ^3F_4]$ via the assistance of phonons. Finally, Pr$^{3+}$ ion exhibits NIR emissions from the $^1D_2$ and $^1G_4$ levels. The whole UV-to-NIR ET process from Eu$^{2+}$ to Pr$^{3+}$ could be expressed as ($^{1a} \rightarrow 2 \rightarrow ^{2c} \rightarrow ^{2d} \rightarrow ^{NIR}$).

4. Conclusion

We have successfully developed a novel NIR phosphor LiSrPO$_4$:Eu$^{2+}$, Pr$^{3+}$, which is a potential solar spectral converter for Si solar cells. This novel NIR DS phosphor has an intense wide excitation bands in the UV-Vis region, harvesting the incident solar spectrum, and exhibits an intense NIR emission of Pr$^{3+}$ around ~1000 nm, perfectly matching the maximum spectral response of Si solar cells. We demonstrate that Eu$^{2+}$/Pr$^{3+}$ ion can be an efficient donor-acceptor pair and Eu$^{2+}$ ion can be an efficient sensitizer harvesting UV photon and greatly enhancing the NIR emission of Pr$^{3+}$ ion through efficient energy feeding by allowed 4f-5d absorption of Eu$^{2+}$ ion with high oscillator strength. From the optical standpoint, it may be a potential spectral converting material to match the solar spectrum and the spectral response of c-Si solar cell. NIR quantum yield measurement would be highly desirable. In future, the as-synthesized phosphor should be combined with Si solar cell in order to prove to what extent it would enhance efficiency of PV device.

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