Spectral conversion for silicon solar cell using $Y_3Al_5O_{12}$:Ce^{3+}, M (M= Yb^{3+} or Nd^{3+}) phosphors

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Abstract

A UV-Visible to near infrared spectral converting phosphor $Y_3Al_5O_{12}$:Ce^{3+}, M (M= Yb^{3+} or Nd^{3+}) has been synthesized by one step combustion synthesis method. The prepared phosphor is characterized by photoluminescence spectrophotometer (UV-VIS) and near infrared (NIR) spectrophotometer. A broad emission around 500-650 nm attributing to 5d→4f transition of Ce^{3+} and a very intense near infrared emission of Yb^{3+} at 1030 nm ascribing to $^2F_{5/2}$ - $^2F_{7/2}$ transition and Nd^{3+} covers the whole NIR region between 850 nm to 1400 nm assign to the $^4I_{9/2,11/2,13/2}$ transitions was observed upon the excitation of Ce^{3+} at 460 nm. An efficient energy transfer mechanism from Ce^{3+} to Yb^{3+} and Ce^{3+} to Nd^{3+} is also proposed. These results demonstrate the possibility for enhancing the photovoltaic conversion efficiency of silicon solar cell by modifying the absorption and utilizing the UV to blue part of the solar spectrum where the efficiency of silicon solar cell is low.

Keywords - Solar cell, Photoluminescence, Energy transfer, Yttrium aluminate garnate (YAG)

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Introduction

Green and renewable energy is the only source capable of generating sufficient energy in order to meet the long-term energy demand world-wide, since the energy production from fossils fuels increasing the greenhouse gases[1]. Sustainable energy production based on direct conversion of the energy radiated by the sun into useful forms of energy is one of the solutions to tackle the increasing greenhouse gases. The photovoltaic cells are the prime candidates for this task, since it has capacity to convert the sunlight into electricity. Unfortunately, at present the contribution of photovoltaic energy is limited due to its conversion efficiency. Currently the commercial solar cell available in the market is the crystalline silicon solar cells with the conversion efficiency just above 15%[2] although, theoretically the maximum efficiency of c-Si solar cells can be reached upto 30%; this is known as Shockley-Queisser limit[3]. Majority of the energy losses (over 70%) are related to the spectral mismatch of the incident solar photons energies to the energy gap (E_g=1.12eV for c-Si solar cell) of a solar cell[4]. Photons of low-energy are not absorbed (transmission losses) while absorption of high-energy photons with the energy excess is transformed into kinetic energy of a generated electron-hole pair, and subsequently converted to heat (thermalization loss). Spectral modification using luminescent materials have been considered as a promising option to boost the efficiency and performance of solar cells[5], and the detailed-balance calculations show that the value could be improved to 39.63% (using downconversion materials) and 47.6% (using up-conversion materials) by suitable spectral modification[6],[7].

Over the years, luminescent materials have attracted a great deal of attention from researchers because of their potential for optical manipulation in fluorescent lamps[8], plasma display panels[9] and white light emitting diodes[10]. The possibility of using luminescent materials for spectral modification can greatly eliminate the spectral mismatch phenomenon by improving the utilization of sunlight, thereby indirectly improving the efficiency and performance of solar cell[4]. Recently, researchers have tried to develop such luminescent materials either as downconversion, downshifting or upconversion materials[11],[12],[13]. However, the up-conversion is a nonlinear optical process where an up-converting luminescent material can generate one high energy photons for every two or more low energy photons[14] whereas the former two are the linear process. In downconversion process one high energy photon can be converted into two

low energy photons with the external efficiency upto 200% can be achieved, while Down-shifting process transform high energy photons into low energy photons and thus its external quantum efficiency cannot exceed unity[15]. In the present work, we explored the efficient down-shifting phenomenon in Ce^{3+} - M^{3+} (Ln = Yb or Nd) co-doped $Y_3Al_5O_{12}$ (YAG) phosphors through efficient energy transfer. The phosphors can efficiently convert UV-blue photons in a broad range from 300 to 500 nm into near infrared emission where the solar cell has better spectral response. Thus this phosphor may have potential applications as spectral convertors to enhance the photoelectric conversion efficiency of c-Si solar cells.

Experimental

Powder samples of $Y_3Al_5O_{12}$ doped with Ce^{3+} and Yb^{3+}/Nd^{3+} were prepared by one step modified combustion synthesis technique[10]. All the starting materials were of Analytical Reagent grade. Rare earths oxides/carbonates/sulfates were converted to the corresponding nitrates by dissolving in nitric acid. The nitrates were dried by prolonged, gentle warming. Stoichiometric amounts of hydrated nitrates of yttrium, aluminum, cerium and ytterbium or neodymium were thoroughly mixed with urea/glycine. The nitrates to fuel ratios were calculated by the method described earlier[16],[17]. Due to the presence of crystallization water in aluminum nitrate, a thick paste was formed. A china dish containing the paste was inserted in a furnace preheated to 500°C. Within minutes the paste foamed and a flame was produced which lasted for several seconds. The china dish was immediately removed from the furnace.

The UV-VIS and NIR photoluminescence (PL) and photoluminescence excitation (PLE) spectra were measured by a Hitachi-F7000 florescence spectrophotometer and Photon Technology International QM-51 NIR spectrophotometer. All the measurements were carried out at room temperature.

Results and Discussion

Figure 1 shows the photoluminescence excitation (PLE) and photoluminescence emission (PL) spectra of $Y_3Al_5O_{12}:Ce^{3+}$, Yb^{3+} with constant Ce^{3+} concentration (0.7 mol%) and different Yb^{3+} concentrations (0.5 mol% to 10 mol%). The PLE spectra are obtained by monitoring the emission of Ce^{3+} at 525 nm and Yb^{3+} at 1030 nm. The PLE spectrum of $Y_3Al_5O_{12}:Ce^{3+}$,Yb^{3+} consists of two excitation band peaks at 340 nm and 460 nm is similar with the literature results[10],[18]. These excitation bands arises due to the first allowed 4f-5d transition of Ce^{3+} ions, from the Ce^{3+} 4f level ($^2F_{5/2}$) to its lowest 5d ($^2A_{1g}$) level. The other excitation band peak at 340 nm is due to the second allowed 4f–5d transition, 4f ($^2F_{5/2}$) → 5d ($^2B_{1g}$), of Ce^{3+} ions. Under excitation at 460 nm, intense emissions both in the VIS and NIR region were observed. The broad emission with the peak at 525 nm can be ascribed to the 5d-4f transition of Ce^{3+}: 5d ($^2A_{1g}$) →4f ($^2F_{5/2}$), while the emission at 1030 nm is attributed to the $^2F_{5/2}$ → $^2F_{7/2}$ transitions of Yb^{3+} ions, respectively. The spectral overlap between the excitation band for Ce^{3+} emission at 525 nm and Yb^{3+} emission at 1030 nm verifies the existence of energy transfer from Ce^{3+} to Yb^{3+}. In order to confirm the energy transfer from Ce^{3+} to Yb^{3+}, the dependence of VIS and NIR emission intensity on the Yb^{3+} concentration is also investigated. As the concentration of Yb^{3+} varied, the PL intensity of Yb^{3+} activator increases and reaches maximum at 5 mol% beyond which the concentration quenching observed, whereas that of the Ce^{3+} sensitizer simultaneously decreased monotonically. This is a direct proof on energy transfer between Ce^{3+} and Yb^{3+}. The inset in Figure 1, presents the dependence of Ce^{3+} any Yb^{3+} emission intensities on Yb^{3+} concentration in $Y_3Al_5O_{12}:Ce^{3+}$, Yb^{3+}.
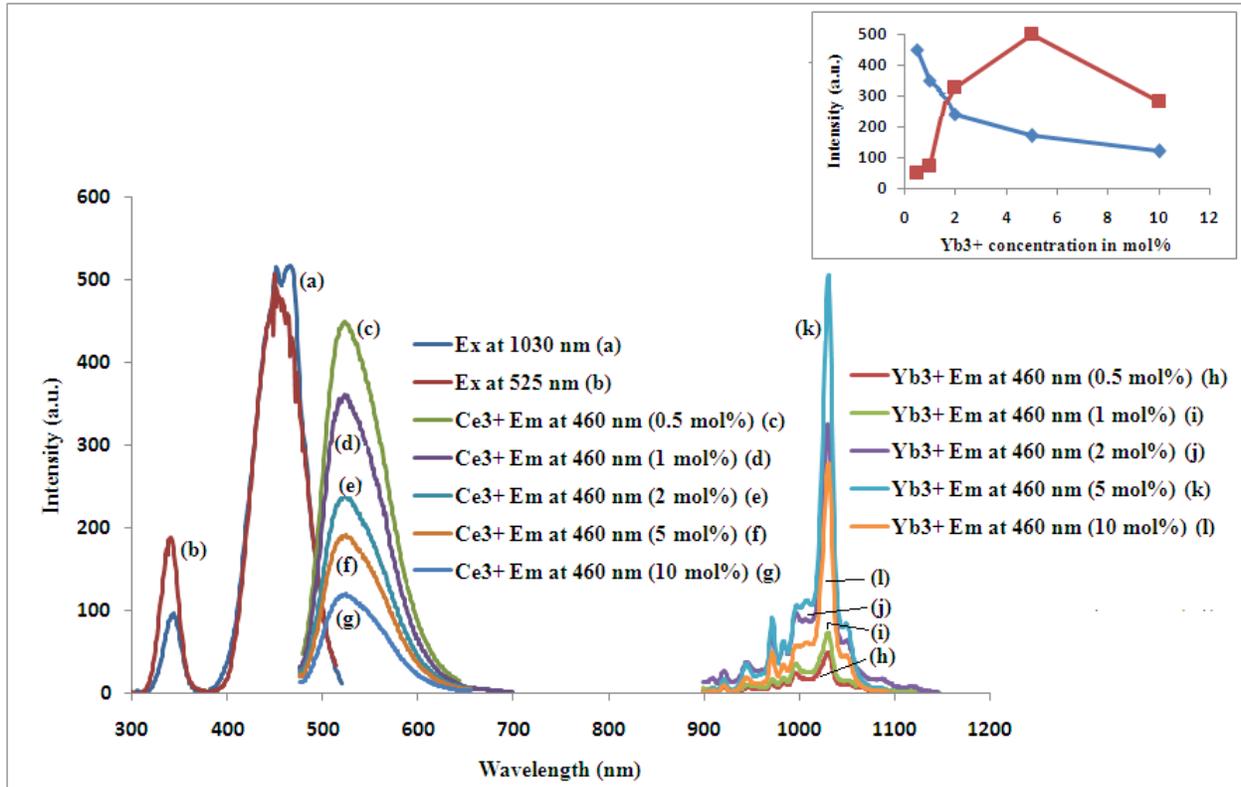
Figure 1. PLE (a, λ_{em} = 525 nm & b, λ_{em} = 1030 nm) and PL (c-g, λ_{ex} = 460 nm) and NIR PL (h-l, λ_{ex} = 460 nm) spectra of $Y_3Al_5O_{12}$:$0.007Ce^{3+}$,xYb^{3+} (x= 0.5 mol% - 10 mol %) phosphors. Inset shows the concentration dependence of PL intensity.

Figure 2 shows the terrestrial solar spectrum (AM 1.5 G), the spectral response of c-Si solar cell and the photoluminescence excitation and emission of $Y_3Al_5O_{12}$:Ce^{3+},Yb^{3+} phosphors. As shown in figure the AM 1.5 G solar spectrum starts from 280 nm 4000 nm (shown upto 1400 nm) and YAG:Ce^{3+},Yb^{3+} has two excitation band at peaked at 340 nm and 460 nm, the position of theses excitation band in the UV and blue region shows a better agreement with the solar spectrum and gives broad emission at 525 nm and an intense NIR emission at 1030 nm, matching well with the optimal spectral response of the c-Si solar cell. This means that YAG:Ce^{3+},Yb^{3+} is suitable for modifying the solar spectrum in order to increase the performance of c-Si solar cell.
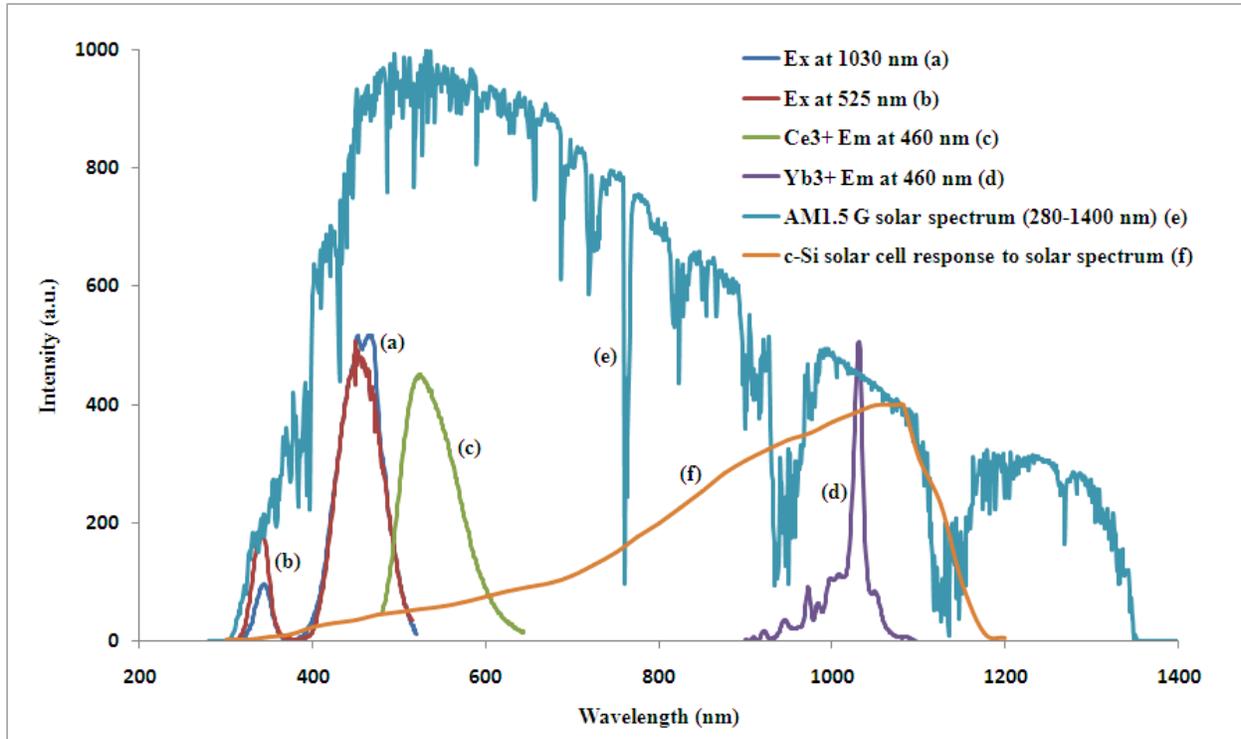
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Figure 2. PLE (a,b) and PL (c,d) spectra of $Y_{2.943}Al_5O_{12}$:0.007Ce^{3+},0.05Yb^{3+} in visible and NIR. (e) AM 1.5 G solar spectrum and (f) spectral response of c-Si solar cell.

A series of $Y_3Al_5O_{12}$:Ce^{3+},Nd^{3+} phosphors with different Nd^{3+} concentration were also prepared and the effect of co-doped Nd^{3+} concentration on the Ce^{3+} and Nd^{3+} emission intensity was investigated. The doping concentration of Ce^{3+} was fixed with 0.7 mol% while the concentration of Nd^{3+} was varied from 1 mol% to 2 mol%. The photoluminescence excitation (PLE) and photoluminescence emission (PL) spectra of Ce^{3+} - Nd^{3+} co-doped $Y_3Al_5O_{12}$ phosphors are shown in Figure 3. Upon excitation at 460 nm, the PL spectra of YAG:Ce^{3+},Nd^{3+} phosphors consists of the broadband emission of Ce^{3+} in the visible region peaked at 525 nm ascribed to the 5d-4f transition of Ce^{3+}: 5d ($^2A_{1g}$) $\rightarrow$4f ($^2F_{5/2}$) were observed. In the NIR region of 800 nm – 1400 nm, three broad and intense emission of Nd^{3+} with the peaks at 893 nm, 1067 nm and 1343 nm assign to $^4I_{9/2,11/2,13/2}$ transitions of Nd^{3+} ions under 460 nm excitation[19]. Thus both the visible and NIR emission were observed with the excitation at 460 nm. Two excitation bands at 340 nm and 460 nm (which is characteristic for YAG:Ce^{3+}) were observed for NIR emission of Nd^{3+} similar to the excitation bands for Ce^{3+} emission at 525 nm. The dependence of Ce^{3+} and Nd^{3+} emission intensities on Nd^{3+} doping concentration in YAG:Ce^{3+},Nd^{3+} are shown

in the insets in Figure 3. It can be observed that, as the concentration of Nd^{3+} increases, the PL intensity of Ce^{3+} emission decreases continuously, whereas the emission intensity of Nd^{3+} increases with concentration reaching maximum at 1.5 mol% and then decreases due to the concentration quenching effect. The spectral overlap of the excitation bands for Ce^{3+} emission at 525 nm and Nd^{3+} emission at 1067 nm and the concentration-dependent quenching of luminescence are attributed to the energy migration from Ce^{3+} to Nd^{3+}.
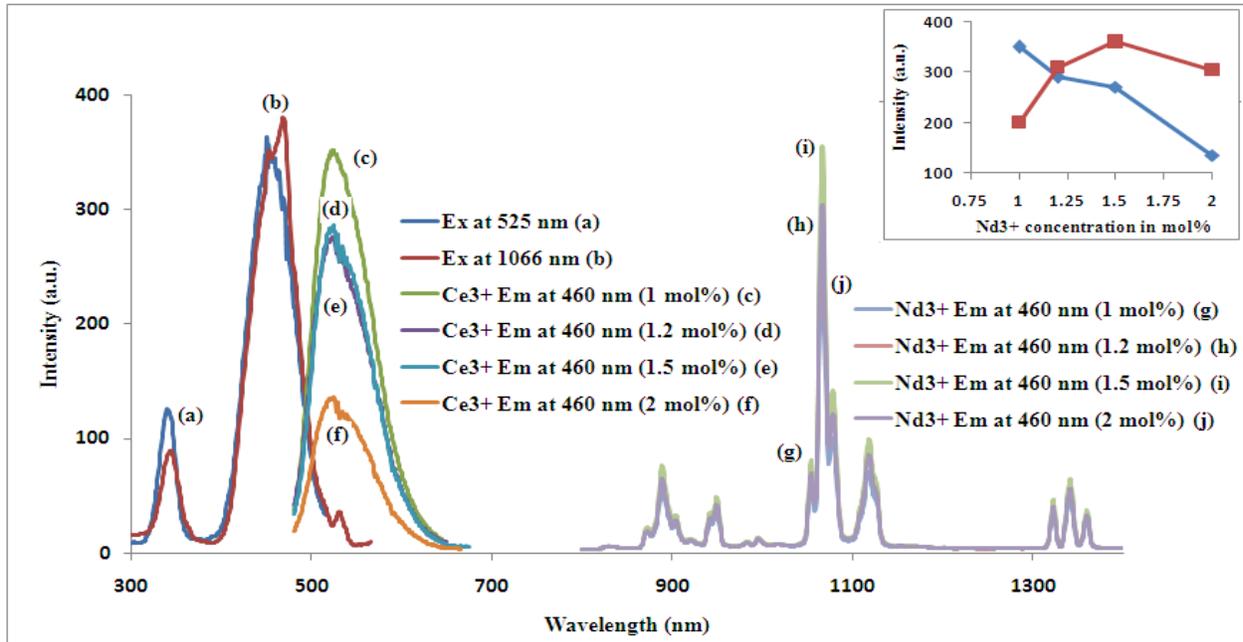

Figure 3. PLE (a, λ_{em} = 525 nm & b, λ_{em} = 1067 nm) and PL (c-f, λ_{ex} = 460 nm) and NIR PL (g-j, λ_{ex} = 460 nm) spectra of $Y_3Al_5O_{12}$:0.007Ce^{3+},xNd^{3+} (x= 1 mol% - 2 mol %) phosphors. Inset shows the concentration dependence of PL intensity.

As discussed earlier in Figure 2, similar observations can be point out for excitation and emission spectra for $Y_3Al_5O_{12}$:Ce^{3+},Nd^{3+} phosphors compared to the solar radiation at AM 1.5 G and the spectral response of c-Si solar cell shown in Figure 4. The positions of the excitation bands is well suited for solar modification with the characteristics NIR emission of Nd^{3+} which can be better utilizes by the c-Si solar cell.
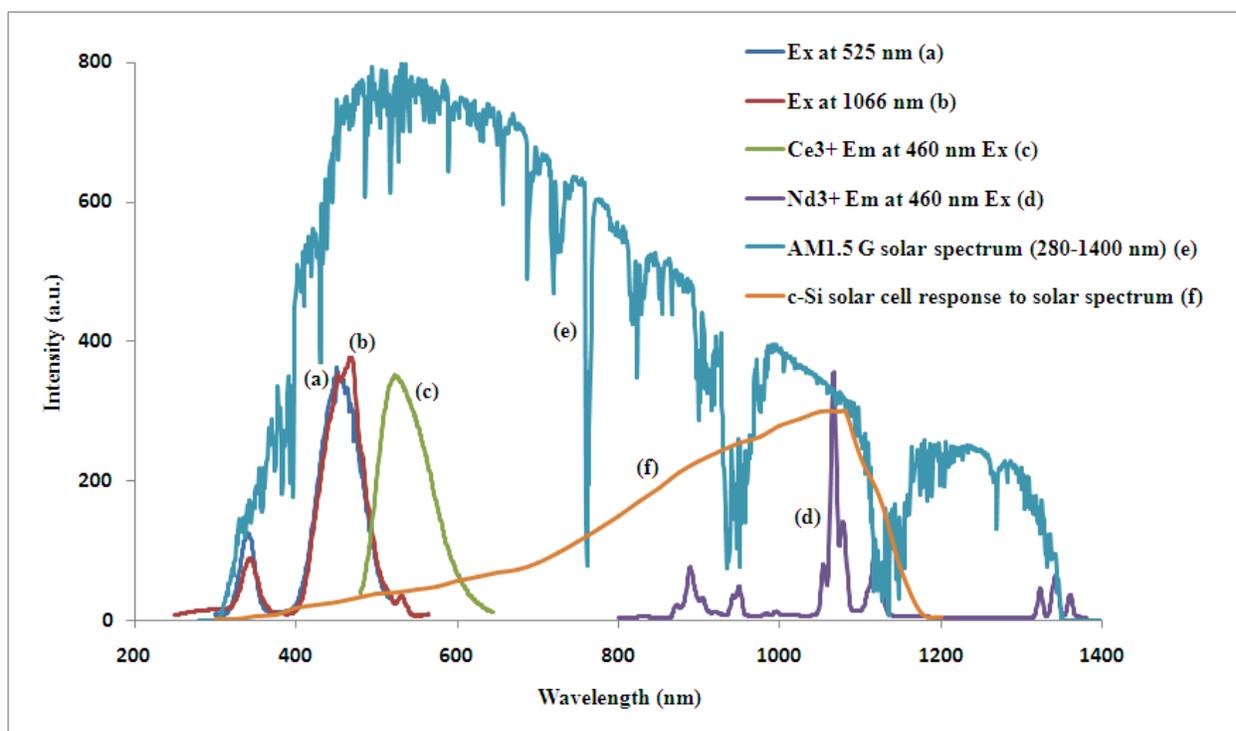
Figure 4. PLE (a,b) and PL (c,d) spectra of $Y_{2.978}Al_5O_{12}{:}0.007Ce^{3+},0.015Nd^{3+}$ in visible and NIR. (e) AM 1.5 G solar spectrum and (f) spectral response of c-Si solar cell.

Conclusions

In summary, an efficient broadband downshifting $Y_3Al_5O_{12}{:}Ce^{3+},M^{3+}$ (M = Yb & Nd) phosphors promising for solar spectrum modification as a down-shifting materials has been successfully developed. The phosphors can efficiently harvest the UV-blue photons and gives an intense NIR emission in the range 800 nm – 1400 nm. The emission and excitation spectra confirmed the occurrence of energy transfer from Ce^{3+} to Yb^{3+}/Nd^{3+} in $Y_3Al_5O_{12}$ phosphors. Therefore, these down-shifting phosphors may have great potential application in c-Si solar cells to enhance the efficiency and performance via spectral modification.

Acknowledgement

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