

Preparation of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ downconversion luminescent material and its application in dye-sensitized solar cells

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$\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ downconversion luminescent powder was prepared using the homogeneous precipitation method. Its optical properties were analyzed and it was introduced into a dye-sensitized solar cell (DSSC). As a luminescence medium, $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ improved light harvesting via conversion luminescence and increased the photocurrent of the DSSC. As a p-type dopant insulating rare earth oxides form an energy barrier, and the $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ elevated the energy level of the oxide film and increased the photovoltage. The photoelectric conversion efficiency for a DSSC with $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ doping (6:100) reached 7.01%, which was 17.4% higher than the photoelectrical conversion efficiency of a DSSC without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ doping.

dye-sensitized solar cell, downconversion, rare-earth oxide, luminescent material, p-type doping

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Considerable effort has been devoted to the dye-sensitized solar cell (DSSC) since the first prototype was reported by O'Regan et al. [1] and Gratzel [2]. There has been great progress in development of the DSSC over the past decade, because of its low cost, simple preparation, and conversion efficiency which has reached 11% [3]. In general, the sensitizer of the DSSC contains mainly N3 and N719 dyes [1–6], and the DSSC consists of a porous nanocrystalline TiO_2 film sensitized by a dye for absorbing incident light. However, even the best of these dyes (N719) absorbs only visible light in the wavelength range 300–800 nm, while the standard air-mass (AM1.5) terrestrial spectrum covers the wavelength region from UV to IR (200–2500 nm). Downconversion materials are a viable option for reducing the spectral mismatch losses. Trupke et al. [7] have suggested that the dye molecules in a DSSC could avoid the absorption of high-energy photons in a conventional semiconductor solar cell with infinite bands, by directing the

high-energy part of the solar spectrum toward a downconverter with suitable low-pass mirrors. However, few studies have been carried out on the use of conversion luminescence in the DSSC. Our group [8] has reported work in which $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor was prepared by the co-precipitation method. As a luminescence medium $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ improved light harvesting via a conversion luminescence process and increased the photocurrent. As a p-type dopant, $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ elevated the energy level of the oxide film and increased the photovoltage.

In the present study, $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor was prepared by the homogeneous precipitation method [9,10]. Since Gd_2O_3 is isostructural with Y_2O_3 , $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ can be used as a phosphor and is comparable to $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$. $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ has been reported to be a more effective phosphor than $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ for particular applications such as an X-ray scintillator, because Gd_2O_3 has higher density and light efficiency [11]. In addition, the synthesis of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ phosphor with higher photoluminescence (PL) intensity than commercially available $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ has been

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reported [12,13]. In the present study, $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ as a luminescence medium and p-type dopant was introduced into the DSSC to improve photocurrent, photovoltage and solar conversion efficiency.

1 Experimental

1.1 Materials

Tetrabutyl titanate, absolute ethyl alcohol, glacial acetic acid, polyethylene glycol 20000, 4-tert-butylpyridine (TBP), nitric acid, OP emulsification agent (Triton X-100), iodine, lithium iodide, urea and ammonium hydroxide were analytical grade materials supplied by Shanghai Chemical Agent Ltd., Shanghai, China. Gadolinium oxide and europium oxide with purity 99.99% and 99.999% respectively, were supplied by Shanghai Yuelong Non-Ferrous Metals Limited, Shanghai, China. The sensitized dye N-719 (RuL2(NCS)₂, L=4,4'-dicarboxylate-2,2'-bipyridine) was from SOLARONIX SA (Aubonne, Switzerland).

1.2 Preparation of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor

$\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor was prepared using the homogeneous precipitation technique by the following procedure [9,10]. Appropriate amounts of Gd_2O_3 and Eu_2O_3 were dissolved in dilute HNO_3 solution. The HNO_3 solution was made from a 1:1 (v/v) mixture of deionized water and 60%–65% HNO_3 solution. After heating and evaporating the excess water and HNO_3 until nitrate crystals emerged, the required amount of water was added to form 0.05 mol/L $\text{Gd}(\text{NO}_3)_3$ and 0.05 mol/L $\text{Eu}(\text{NO}_3)_3$ aqueous solutions. The required volumes of the $\text{Gd}(\text{NO}_3)_3$ and $\text{Eu}(\text{NO}_3)_3$ solutions were then mixed to give a solution with the mole ratio $\text{Gd}(\text{NO}_3)_3:\text{Eu}(\text{NO}_3)_3=100:6$. Excess 0.2 mol/L urea solution was mixed with the $\text{Gd}(\text{NO}_3)_3/\text{Eu}(\text{NO}_3)_3$ solution, and sufficient aqueous ammonium hydroxide was added to adjust the pH to 8–9. The resulting solution was heated in a water bath at 90°C, and refluxed for 5 h after a precipitate started to form. The reaction mixture was then quenched in ice water, the precipitated precursor powder was washed with water and ethyl alcohol to eliminate residual salts. The powder was vacuum dried at 80°C for 24 h, then calcined at 800°C for 2 h, for subsequent use as a nanophosphor.

1.3 Preparation of film electrodes of DSSC

A TiO_2 colloid was prepared according to the method developed by our group [14–17]. Varying amounts of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor were dispersed in TiO_2 sol, ultrasonicated and stirred for 30 min, then hydrothermally treated to form a $\text{TiO}_2+\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ colloid. A film with thickness about 12 μm was prepared by coating TiO_2 colloid on a fluorine doped tin oxide coated glass (FTO) using a doctor blade and sintering at 450°C for 30 min, then a

$\text{TiO}_2+\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ layer with thickness of about 4 μm was coated on the TiO_2 film by the same method. After sintering at 450°C for 30 min and soaking in N-719 dye solution for 24 h, a dye sensitized film electrode ($\text{TiO}_2+\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$) was obtained. For comparison, a dye-sensitized TiO_2 film electrode without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ was also made. The thickness of the oxide films for the DSSC with and without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ were about 16 μm . DSSCs with and without the $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ bearing layer were assembled using the methods described previously [17].

1.4 Characterization and measurements

Powder X-ray diffraction (XRD) patterns were recorded with an X-ray diffractometer (Bruker D8, Karlsruhe, Germany) using $\text{Cu K}\alpha$ radiation ($\lambda=1.5405 \text{ \AA}$). Micrographs were recorded using a field emission scanning electron microscope (SEM, S-4800, Hitachi, Japan). Photoluminescence spectra were obtained using a fluorescence spectrometer (FLS920, with excitation wavelength 263 nm, Edinburgh Instruments, UK). Photovoltaic tests of DSSCs were carried out by measuring the $I-V$ characteristic curves under simulated solar light irradiation of 100 mW/cm^2 from a 100 W Xe lamp (XQ-500W, Shanghai Photoelectricity Device Company, Shanghai, China).

Mott-Schottky analysis was carried out using standard electrochemical impedance spectroscopy at 1000 Hz in acetonitrile solution of containing 0.1 mol/L lithium perchlorate, 10 mmol/L lithium iodide and 1 mmol/L iodine, by scanning the potential from the positive to the negative direction in steps of 5 mV/s at room temperature. The TiO_2 thin film on FTO glass was the photoanode, the cathode was Pt foil, and a silver/silver chloride (Ag/AgCl) microelectrodes was used as reference electrode.

2 Results and discussion

2.1 $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor

Figure 1 shows a typical XRD pattern of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ phosphor calcined at 800°C in air. It is basically consistent with the standard X-ray diffraction card JCPDS 12-0797 without any impurity peaks, indicating Gd_2O_3 with pure cubic structure. An SEM image of the powders is shown in Figure 2, and reveals that the particle size was 30–60 nm.

2.2 The properties of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor

Excitation spectra and emission spectra of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor are shown in Figures 3 and 4. The spectral properties are typical of the well-known $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ [18–20]. The excitation spectrum was obtained by monitoring the emission of the $\text{Eu}^{3+} {}^5\text{D}_0 \rightarrow {}^7\text{F}_2$ transition at 611 nm. It can be seen clearly that the excitation spectrum (Figure 3) consists of a broad band with a maximum at 256 nm due to

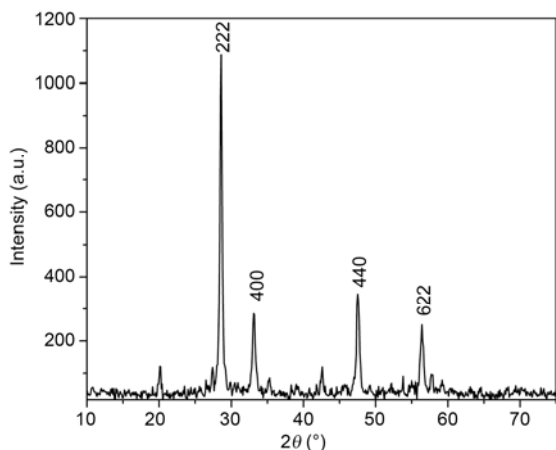


Figure 1 XRD pattern of the prepared $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor.

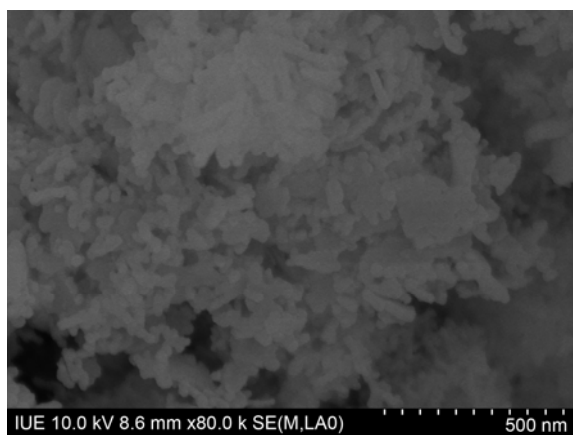


Figure 2 The SEM picture of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor.

the charge-transfer band (CTB) between O^{2-} and Eu^{3+} . The sharp peaks at 308 nm and the weak shoulder at 275 nm superimposed on the CTB of Eu^{3+} can be attributed to the Gd_2O_3 host excitation band, the $^8\text{S}-^6\text{P}$, and $^8\text{S}-^6\text{I}$ transition lines of Gd^{3+} , respectively [21]. The presence of the Gd_2O_3 host band and Gd^{3+} excitation lines in the excitation spectrum of Eu^{3+} indicates that there is energy transfer from the Gd_2O_3 host and Gd^{3+} to Eu^{3+} . In the longer wavelength region, the f-f transition lines of Eu^{3+} (assigned in Figure 3) can be observed with very weak intensity compared with the $\text{Eu}^{3+}-\text{O}^{2-}$ CTB. Upon excitation into the CTB of Eu^{3+} at 263 nm, the resulting emission spectrum is composed of $^5\text{D}_{0,1,2} \rightarrow ^7\text{F}_J$ ($J=0, 1, 2, 3, 4$) transition lines of Eu^{3+} , with the $^5\text{D}_0 \rightarrow ^7\text{F}_2$ hypersensitive transition (611 nm) being the most prominent group (Figure 4). All of the other emission peaks at 534 ($^5\text{D}_1 \rightarrow ^7\text{F}_1$), 580 ($^5\text{D}_0 \rightarrow ^7\text{F}_0$), 588, 593, 599 ($^5\text{D}_0 \rightarrow ^7\text{F}_1$), 651 ($^5\text{D}_0 \rightarrow ^7\text{F}_3$), and 708 nm ($^5\text{D}_0 \rightarrow ^7\text{F}_4$) are assigned in Figure 4. The presence of emission lines from higher excited states of Eu^{3+} ($^5\text{D}_1$, $^5\text{D}_2$) is attributed to the low vibration energy of the Gd-O band (545 cm^{-1}). Multiphonon relaxation by Gd-O vibration is not able to completely bridge the gaps

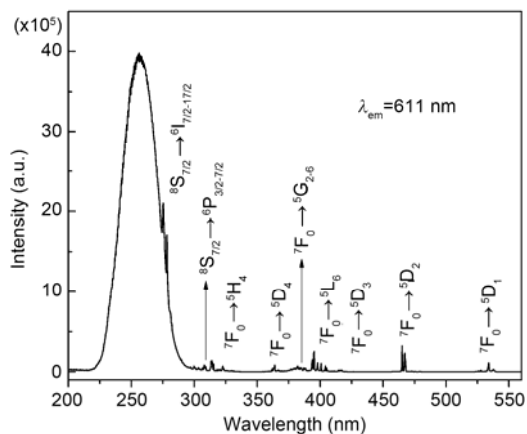


Figure 3 The excitation spectra of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor.

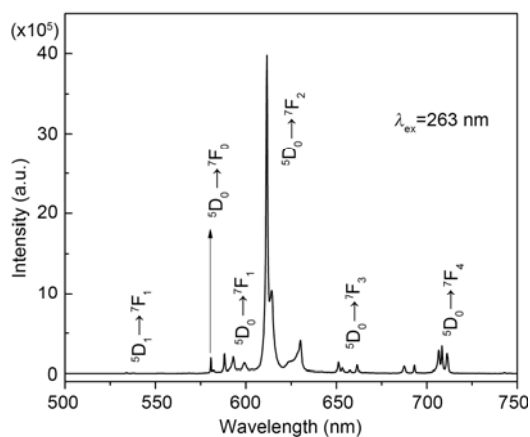


Figure 4 The emission spectra of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor.

between the higher energy levels ($^5\text{D}_1$, $^5\text{D}_2$) and the $^5\text{D}_0$ level of Eu^{3+} , resulting in the emission from these levels [21].

2.3 Photoelectric performance of DSSC

To investigate the effect of ultraviolet irradiation, we used a filter (ZWB3) that only the light with wavelength less than 420 nm could pass through. Figures 5 and 6 show the photocurrent-voltage curves of DSSCs and the solar cells with no dye, and with and without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ in TiO_2 the electrode under the ultraviolet irradiation of 24 mW/cm^2 . Figure 5 shows that the DSSC lacking the rare-earth ions as dopant had the following photovoltaic parameters: short-circuit current density (J_{SC})= 1.05 mA/cm^2 , open-circuit voltage (V_{OC})= 0.591 V , fill factor (FF)= 0.569 and light-to-electric energy conversion efficiency (η)= 1.47% . The DSSC containing the rare-earth ions as dopant displayed the enhanced photovoltaic parameters: J_{SC} = 1.19 mA/cm^2 , V_{OC} = 0.679 V , FF = 0.565 and η = 1.90% . Figure 6 indicates that with no dye in the solar cells, the cells lacking the rare-earth ions as dopant had the photovol

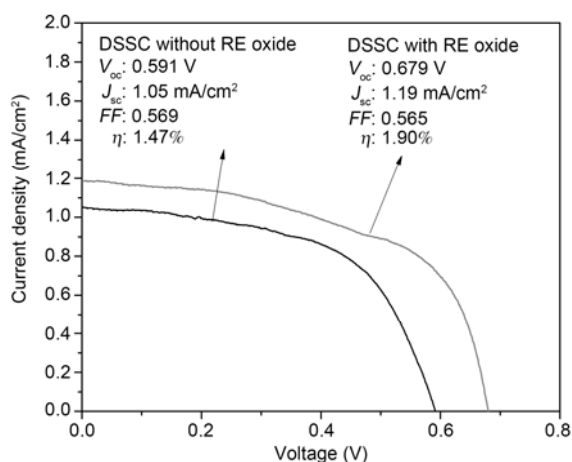


Figure 5 Current-Voltage curves of DSSCs under ultraviolet irradiation (24 mW/cm^2).

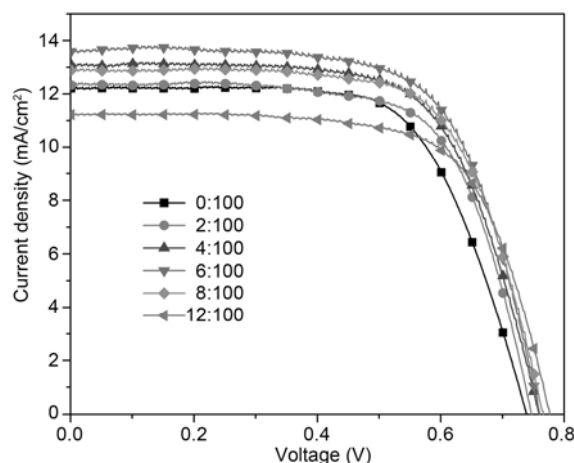


Figure 7 Current-Voltage curves of DSSCs without and with different ratio of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor in TiO_2 electrode.

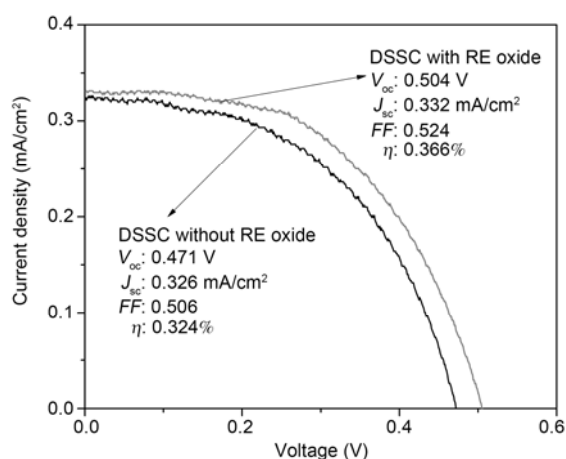


Figure 6 Current-Voltage curves of the solar cells when no dye under ultraviolet irradiation (24 mW/cm^2).

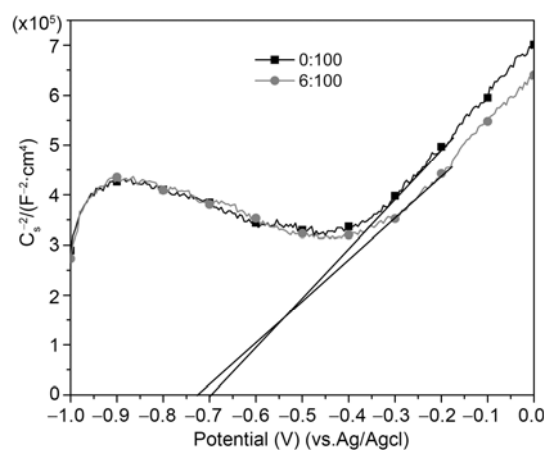


Figure 8 Mott-Schottky plots of TiO_2 electrode with and without doped nanophosphor.

taic parameters: $J_{\text{SC}}=0.326 \text{ mA/cm}^2$, $V_{\text{OC}}=0.471 \text{ V}$, $FF=0.506$ and $\eta=0.324\%$. The solar cells containing the rare-earth ions as dopant displayed the enhanced photovoltaic parameters: $J_{\text{SC}}=0.332 \text{ mA/cm}^2$, $V_{\text{OC}}=0.504 \text{ V}$, $FF=0.524$ and $\eta=0.366\%$. The enhancement indicates that the rare-earth ions dopant converts ultraviolet light to visible light which the N-719 dye can absorb effectively, increasing the harvested sunlight and improving the efficiency of the DSSC.

The data in Figure 7 and Table 1 show that J_{SC} increased with the $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ dopant level up to 6:100 (the mole ratio of gadolinium and titanium), beyond which J_{SC} decreased. The increase in J_{SC} comes mainly from the ultraviolet response of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor, which caused more to be harvested, thus increasing J_{SC} . The decrease in J_{SC} at higher dopant levels is due to the fact that introduction of rare-earth oxides produced defects in the oxide film, which caused the recombination of photoinduced holes and electrons and hence decrease J_{SC} [22].

Figure 8 is a Mott-Schottky plot for the TiO_2 electrode

with and without doped nanophosphor. It is clear from Figure 8 that under the same conditions, the TiO_2 working electrode of TiO_2 had similar flatband potential with (-0.723 V) or without (-0.692 V) nanophosphor. Figure 8 also shows that the slope of the linear region of the Mott-Schottky curve decreased when the nanophosphor was doped, thus increasing its charge carriers density.

On the other hand, the V_{OC} increased with increasing amount of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$. When the mole ratio of element gadolinium and titanium was 12:100, V_{OC} reached 0.776 V , which is the highest value yet observed in a DSSC, indicating the significance of p-type doping. According to Gratzel [2], V_{OC} corresponds to the difference between the energy level of the electrons in the oxide film and the redox potential of the electrolyte. When rare-earth ions are doped and substitute for the Ti^{4+} ion lattice sites in TiO_2 , giving a p-type doping similar to that in Si semiconductors, the energy level of the oxide film is elevated, which leads to the increase of V_{OC} . Similar phenomena were observed by Ko et al.

Table 1 Influence of $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor on photoelectric parameters of DSSC

Mole ratio ($N_{\text{Gd}}:N_{\text{Ti}}$)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
0:100	12.30	0.739	0.657	5.97
2:100	12.47	0.747	0.677	6.31
4:100	13.18	0.759	0.667	6.68
6:100	13.79	0.76	0.669	7.01
8:100	12.93	0.766	0.685	6.78
12:100	11.25	0.776	0.687	5.99

[23] who found that Al-doping of the TiO_2 electrode increased V_{oc} , while W-doping had the opposite effect (n-type doping). Yang et al. [24,25] found that an energy barrier was formed when the TiO_2 electrode was modified with a rare earth ion layer of a certain thickness. The energy barrier efficiently suppressed charge recombination. As a result, the photovoltage and photoelectrical conversion efficiency were improved under optimal conditions.

The solar conversion efficiency for a DSSC with $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ (6:100) doped nanophosphor reached 7.01%, which is 17.4% higher than for a DSSC without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor doping (Figure 7). Furthermore, by choosing a suitable doping ion and concentration as a p-type luminescence medium, it is possible to further increase the conversion efficiency of the DSSC.

3 Conclusion

In summary, $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor was introduced into a dye-sensitized solar cell. As a luminescence medium, $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ improved light harvesting via a conversion luminescence process and increased photocurrent. As a p-type dopant insulating rare earth oxides form an energy barrier, and the $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ elevated the energy level of the oxide film and increased the photovoltage. The solar conversion efficiency for a DSSC with $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ doping (6:100) reached 7.01%, which is 17.4% higher than for a DSSC without $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanophosphor doping.

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- O'Regan B, Gratzel M. A low-cost high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films. *Nature*, 1991, 353: 737–740
- Gratzel M. Photoelectrochemical cells. *Nature*, 2001, 414: 338–345
- Gratzel M. Solar energy conversion by dye-sensitized photovoltaic cells. *Inorg Chem*, 2005, 44: 6841–6851
- Gratzel M. Engineering of a novel ruthenium sensitizer and its application in dye-sensitized solar cells for conversion of sunlight into electricity. *Inorg Chem*, 2005, 44: 178–180

- Lee S A, Abrams N M, Hoertz P G, et al. Compling of titania inverse opals to nanocrystalline titania layers in dye-sensitized solar cells. *J Phys Chem B*, 2008, 112: 14415–14421
- Nazeeruddin M K, Kay A, Rodicio I, et al. Conversion of light to electricity by cis-bis (2,2'-bipyridyl-4,4-dicarboxylate) ruthenium (II) charge-transfer sensitizers ($X=\text{Cl}^-$, Br^- , I^- , CN^- and SCN^-) on nanocrystalline TiO_2 electrodes. *J Am Chem Soc*, 1993, 115: 6382–6390
- Trupke T, Green M A, Wurfel P. Improving solar cell efficiency by down-conversion of high-energy photons. *J Appl Phys*, 2002, 92: 1668–1674
- Wu J H, Xie G X, Lin J M, et al. Enhancing photoelectrical performance of dye-sensitized solar cell by doping with europium-doped yttria rare-earth oxide. *J Power Sources*, 2010, 195: 6937–6940
- Park I Y, Kim D J, Lee J W, et al. Effects of urea concentration and reaction temperature on morphology of gadolinium compounds prepared by homogeneous precipitation. *Mater Chem Phys*, 2007, 106: 149–157
- Liu G X, Hong G Y, Sun D X, et al. Preparation of spherical nanometer $\text{Gd}_2\text{O}_3:\text{Eu}$ luminescent materials (in Chinese). *Chinese J Inorg Chem*, 2004, 20: 1367–1370
- Garcia-Murillo A, Luyer C L, Dujardin C, et al. Elaboration and scintillation properties of Eu^{3+} -doped Gd_2O_3 and Lu_2O_3 sol-gel films. *Nucl Inst Methods Phys Res Sec A*, 2002, 486: 181–185
- Park J C, Moon H K, Kim D K, et al. Morphology and cathodoluminescence of Li-doped $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$, a red phosphor operating at low voltages. *Appl Phys Lett*, 2000, 77: 2162–2164
- Lim M A, Kang Y C, Park H D, et al. $\text{Gd}_2\text{O}_3:\text{Eu}$ phosphor particles prepared from the polymeric precursors in spray pyrolysis. *J Electrochem Soc*, 2001, 148: H171–H175
- Wu J H, Hao S C, Lin J M, et al. Crystal morphology of anatase titania nanocrystals used in dye-sensitized solar cell. *Cryst Growth Des*, 2008, 8: 247–252
- Lan Z, Wu J H, Lin J M, et al. Influence of molecular weight of PEG on the property of polymer gel electrolyte and performance of quasi-solid-state dye-sensitized solar cells. *Electrochim Acta*, 2007, 52: 6673–6678
- Hao S C, Wu J H, Fan L Q, et al. The influence of acid treatment of TiO_2 porous film electrode on photoelectric performance of dye-sensitized solar cell. *Sol Energy*, 2004, 76: 745–750
- Zhang X K, Wu J H, Li S Q, et al. Preparation of nano-crystalline TiO_2 porous film electrode using a mixing P25 hydrothermal method. *Chinese J Imag Sci Photochem*, 2008, 26: 499–506
- Kang Y C, Park S B, Lenggono I W, et al. $\text{Gd}_2\text{O}_3:\text{Eu}$ phosphor particles with sphericity, submicron size and non-aggregation characteristics. *J Phys Chem Solids*, 1999, 60: 379–384
- Garcia-Murillo A, Luyer C L, Dujardin C, et al. Elaboration and characterization of Gd_2O_3 waveguiding thin films prepared by the sol-gel process. *Opt Mater*, 2001, 16: 39–46
- Yang J, Li C X, Cheng Z Y, et al. Size-tailored synthesis and luminescent properties of one-dimensional $\text{Gd}_2\text{O}_3:\text{Eu}^{3+}$ nanorods and microrods. *J Phys Chem C*, 2007, 111: 18148–18154
- Blasse G, Grabmaier B C. *Luminescent Materials*. Berlin: Springer-Verlag, 1994
- Liu Y, Shen H, Huang X R, et al. A new improved structure of dye-sensitized solar cells with reflection film. *Chinese Sci Bull*, 2006, 51: 369–373
- Ko H K, Lee Y C, Jung Y J. Enhanced efficiency of dye-sensitized TiO_2 solar cells (DSSC) by doping of metal ions. *J Colloid Interface Sci*, 2005, 283: 482–487
- Yang S M, Kou H Z, Wang L, et al. Photoelectrochemical properties of N3 sensitized Ho^{3+} modified TiO_2 nanocrystalline electrodes. *Acta Phys Chim Sin*, 2009, 25: 1219–1224
- Yang S M, Li F Y, Huang C H. Photoelectrochemical properties of dye sensitized rare-earth ions modified TiO_2 nanocrystalline electrodes. *Sci China Ser B-Chem*, 2003, 33: 59–65

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