Research Article

The Photoluminescence Behaviors of a Novel Reddish Orange Emitting Phosphor $\text{CaIn}_2\text{O}_4\text{:Sm}^{3+}$ Codoped with Zn^{2+} or Al^{3+} Ions

Jing Gou,¹ Dongyang Zhang,¹ Binxun Yu,² Jing Wang,¹ and Shengzhong Liu¹

¹School of Materials Science and Engineering, Shaanxi Normal University, Key Laboratory of Applied Surface and Colloid Chemistry of Ministry of Education, Xi'an 710119, China

²School of Chemistry and Chemical Engineering, Shaanxi Normal University, Xi'an 710119, China

Correspondence should be addressed to Jing Gou; goujing@snnu.edu.cn

Received 1 December 2014; Revised 26 December 2014; Accepted 29 December 2014

Academic Editor: Yuanlie Yu

Copyright © 2015 Jing Gou et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A novel reddish orange phosphor $\text{CaIn}_2\text{O}_4\text{:Sm}^{3+}$ codoped with Zn^{2+} or Al^{3+} ions was prepared by solid state reaction and their luminescence properties were investigated under near ultraviolet excitation. The strategy of Zn^{2+} or Al^{3+} ions codoping was used with the aim to improve the luminescence properties of $\text{CaIn}_2\text{O}_4\text{:Sm}^{3+}$, but the concrete effects of the two ions is different. The introduction of Zn^{2+} ions can produce Zn_{In}' defects that favor charge balance in $\text{CaIn}_2\text{O}_4\text{:Sm}^{3+}$ to facilitate its photoluminescence. The effect of Al^{3+} ions codoping can effectively transfer energy from charge-transfer absorption band to characteristic transition of Sm^{3+} ions, utilizing more energy from host absorption for the photoluminescence of Sm^{3+} ions. Based on these mechanisms, the luminescence intensity of $\text{CaIn}_2\text{O}_4\text{:0.6%Sm}^{3+}$ was enhanced to 1.59 times and 1.51 times when codoping amount of Zn^{2+} and Al^{3+} ions reached 0.6%. However, the chromaticity coordinates of $\text{CaIn}_2\text{O}_4\text{:0.6%Sm}^{3+}$ almost did not have any changes after Zn^{2+} ions or Al^{3+} ions codoping; those are still located at reddish orange region. The excellent luminescence properties of $\text{CaIn}_2\text{O}_4\text{:0.6%Sm}^{3+}$, 0.6%Zn^{2+} and $\text{CaIn}_2\text{O}_4\text{:0.6%Sm}^{3+}$, 0.6%Al^{3+} demonstrate that they both have potential application value as new-style reddish orange phosphors on light-emitting diode.

1. Introduction

White light-emitting diodes (WLEDs), with the advantages of long lifetime, less energy consumption, and environment friendly characteristics, are thought to be the most important solid state light sources for substituting the widely used incandescent lamps and fluorescent lamps [1–5]. But it still needs to overstep many technological obstructions. It is well known that WLEDs can be realized by combing a single near ultraviolet (NUV, 370–410 nm) light-emitting diodes (LEDs) chip with tricolor phosphors or combining a simple blue LEDs chip with yellow phosphor [6]. With the development of semiconductor technology, NUV-LEDs chips can offer a higher efficient solid state light. Thus the corresponding phosphors which can be efficiently excited by NUV urgently needed to be explored, but the red phosphor excited by

NUV light is rare at present. In last decade, many scientists have been devoted to the red phosphors doped by Eu^{3+} and Eu^{2+} [7–9]. However, commercial red phosphors (e.g., $\text{Y}_2\text{O}_2\text{S:Eu}^{3+}$, CaS:Eu^{2+} , and SrS:Eu^{2+}) do not have enough absorption in the NUV region and the lifetime of the LEDs is limited because of the degradation of these sulfide phosphors during LEDs operation [8].

Sm^{3+} ion is widely used as activator of reddish orange emission due to its $^4\text{G}_{5/2}-^6\text{H}_J$ ($J = 5/2, 7/2, 9/2, 11/2$) transitions, which is the most suitable source for lighting and display from a practical viewpoint [10–12]. CaIn_2O_4 is a semiconductor with band gap (E_g) as 3.9 eV, belonging to ordered CaFe_2O_4 structures with the *Pca*21 or *Pbcm* space group, and the lattice parameters $a = 9.70 \text{ \AA}$, $b = 11.30 \text{ \AA}$, and $c = 3.21 \text{ \AA}$ for $Z = 4$ (Z is the number of formula units per unit cell)

[5, 13]. InO_6 octahedra connect to each other by sharing edges and corners to form a tunnel network structure and Ca^{2+} ions locate in the tunnels. The ionic radius of six-coordinated Sm^{3+} (0.958 Å) is similar to that of Ca^{2+} (1.14 Å) but larger than that of In^{3+} (0.94 Å), so Sm^{3+} ions more easily occupy Ca^{2+} sites in the tunnel of InO_6 octahedra. So far the luminescence properties of $\text{CaIn}_2\text{O}_4:\text{Tb}^{3+}$, $\text{CaIn}_2\text{O}_4:\text{Pr}^{3+}$, $\text{CaIn}_2\text{O}_4:\text{Dy}^{3+}$, and $\text{CaIn}_2\text{O}_4:\text{Eu}^{3+}$ under UV and VUV (vacuum ultraviolet) excitation have been investigated for the application on field emission displays (FEDs), cathode ray tube display (CRTs), and WLEDs [14–16]. To the best of our knowledge, there are few reports about the luminescence properties of $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$ for WLEDs application. Yan et al. reported the photoluminescence of $\text{CaIn}_2\text{O}_4:\text{Eu}^{3+}, \text{Sm}^{3+}$. The doped Sm^{3+} can sensitize the emission of Eu^{3+} and be effective to extend and strengthen the absorption of near-UV light with wavelength of 400–405 nm. The temperature quenching effect proved that CaIn_2O_4 has good stability. And doping amount variation of Sm^{3+} can tune the CIE chromaticity coordinates of $\text{CaIn}_2\text{O}_4:\text{Eu}^{3+}, \text{Sm}^{3+}$ better than conventional red phosphor $\text{Y}_2\text{O}_2\text{S}:0.05\text{Eu}^{3+}$ under the excitation of NUV light [17]. Thus the research about the luminescence properties of $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$ under NUV excitation is very significant. So, in our paper, the luminescence properties of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ codoped with Zn^{2+} or Al^{3+} ions were investigated in detail for basic research and potential application in WLEDs.

2. Experimental Details

The powder samples $\text{CaIn}_2\text{O}_4:x\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Al}^{3+}$ were prepared by solid state reactions [14–16]. The purity of CaCO_3 and In_2O_3 are A.R., while Sm_2O_3 , ZnO and Al_2O_3 are better than 99.99%. Stoichiometric amounts of the starting reagents were thoroughly mixed and ground together. Then the mixture was heated at 1150°C for 12 h. Finally the samples were naturally cooled to room temperature in the furnace.

The normal crystal structure was characterized using $\text{Cu K}\alpha$ radiation (DX-2700 powder X-ray diffractometer) over the angular range $10^\circ \leq \theta \leq 80^\circ$. The UV photoluminescence (PL) and photoluminescence excitation (PLE) spectra were recorded by F-7000 fluorescence spectrophotometer with Xe lamp as the light source. The quantum efficiencies were measured by FLS920 Fluorescence Spectrometer. All above spectra were recorded at room temperature.

3. Results and Discussion

$\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ was characterized by the powder X-ray diffractometer and corresponding powder X-ray diffraction (XRD) patterns are demonstrated in Figure 1 as a sample. It is obvious that most diffraction peaks can be indexed with the Joint Committee on Powder Diffraction Standards (JCPDS) card number 17-0643 indicating that it is almost single-phase structure. That also corresponds to XRDs reported in [13–16]. While there is a little different peak located at 30.6° , which is attributed to the diffraction peak of In_2O_3 , the little

FIGURE 1: XRD patterns of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ and the JCPDS card number 17-0643.

FIGURE 2: The PL spectra of $\text{CaIn}_2\text{O}_4:x\text{Sm}^{3+}$ ($0.2\% \leq x \leq 0.8\%$) ($\lambda_{\text{ex}} = 407 \text{ nm}$).

impurity cannot play an important role in their luminescence properties.

PL spectra of $\text{CaIn}_2\text{O}_4:x\text{Sm}^{3+}$ phosphors with different Sm^{3+} concentrations are shown in Figure 2. As can be seen from these figures, the emission intensity initially increases with Sm^{3+} concentration increasing and reaches a maximum at 0.6 mol% Sm^{3+} and then decreases which resulted from concentration quenching, because nonradiative energy transfer from one Sm^{3+} ion to another takes place. According to [18, 19], the probability of energy transfer among Sm^{3+} ions increases when the Sm^{3+} concentration increases. Nonradiative energy transfer from one Sm^{3+} ion to another usually may occur by exchange interaction, radiation reabsorption, or

multipole-multipole interaction. For $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$, the concentration quenching is caused by the electric multipole-multipole interaction. We can roughly estimate the critical distance of energy transfer (R_c). The distance at which the probability of transfer is equal to the probability of radiative emission can be made using the relation by Blasse to calculate R_c between activator ions of the kind doped in a host lattice:

$$R_c \approx 2 \left[\frac{3V}{4\pi x_c Z} \right]^{1/3}, \quad (1)$$

where V is the volume of the unit cell, x_c the critical concentration of activator ion, and Z the number of formula units per unit cell [20]. For CaIn_2O_4 host, using $Z = 4$, $x_c = 0.6 \text{ mol\%}$, and $V = 351.85 \text{ \AA}^3$, the obtained R_c value is $30.37 \text{ \AA}$. Therefore, the energy transfer in the present case also occurs by electric multipole-multipole interaction.

The PLE and PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Al}^{3+}$ are compared in Figures 3 and 4, respectively. The PLE spectra are monitored by 606 nm . In PLE spectra, the excitation bands from 200 nm to 275 nm with a maximum at 225 nm belong to charge-transfer absorption band (CTB) of O^{2-} ions to Sm^{3+} ions. In the longer wavelength region, the $f-f$ transitions within the $\text{Sm}^{3+} 4f^5$ configuration can be detected, which is assigned as transition from the ${}^6\text{H}_{5/2}$ ground state to the corresponding excited state of Sm^{3+} . Among these sharp lines, the strongest peak centered at 407 nm is assigned to ${}^6\text{H}_{5/2} - {}^4\text{K}_{11/2}$. It is obviously shown that $0.2\%\text{Zn}^{2+}$ codoping can increase the characteristic transitions and CTB of Sm^{3+} ions. In CaIn_2O_4 matrix, the ionic radius of Zn^{2+} ion is $0.88 \text{ \AA}$, similar to that of In^{3+} ion ($0.94 \text{ \AA}$), so Zn^{2+} ion mainly occupies the In^{3+} ion sites. When Sm^{3+} ions replace Ca^{2+} ions in CaIn_2O_4 , it causes the defects V_{Ca}'' and $\text{Sm}_{\text{Ca}}\cdot$ defects occur, which is to the disadvantage of photoluminescence. The introduction of small amount of Zn^{2+} ions can favor the charge balance in $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$ and further facilitate its photoluminescence. The enhanced Sm^{3+} emission comes mainly from radiative recombination of the large amount of trapped carriers excited from the CaIn_2O_4 host. Upon photoexcitation, more oxygen holes can be trapped at the Zn_{In}' defects in $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+},\text{Zn}^{2+}$. The increased recombination probability of electrons and trapped holes would cause the highly enhanced emission intensity of Sm^{3+} ions by the resultant energy transfer to the Sm^{3+} ions nearby. It also could be assumed that the incorporation of Zn^{2+} ions creates the oxygen vacancies, which might act as the sensitizer for the energy transfer to the rare earth ion due to the strong mixing of charge transfer states resulting in the highly enhanced luminescence. However, there is one different PLE spectrum with $0.2\%\text{Al}^{3+}$ ions codoping. When the intensities of characteristic transitions of Sm^{3+} ions increase by a little amount of Al^{3+} ions codoping, the CTB intensities decrease. In $\text{ZnNb}_2\text{O}_4:\text{Dy}^{3+},\text{Al}^{3+}$ material, the fact that energy can be transferred from CTB to excitation states of Dy^{3+} ions by codoping with Al^{3+} ions has been reported [21]. Thus Al^{3+}

FIGURE 3: The PLE spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Al}^{3+}$ ($\lambda_{\text{em}} = 606 \text{ nm}$).

FIGURE 4: The PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Al}^{3+}$ ($\lambda_{\text{ex}} = 407 \text{ nm}$).

ions also can help energy transfer from CTB to characteristic transitions of Sm^{3+} in CaIn_2O_4 matrix.

In the corresponding PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+},0.2\%\text{Al}^{3+}$, all emission peaks are obtained by 407 nm excitation and indexed in Figure 4. It is clearly shown that the little amount of Zn^{2+} or Al^{3+} ions codoping can enhance the intensity of photoluminescence, which corresponds to the PLE

FIGURE 5: The PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Gd}^{3+}$ ($0 \leq y \leq 0.8\%$) ($\lambda_{\text{ex}} = 407 \text{ nm}$).

FIGURE 6: The PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Zn}^{2+}$ ($0 \leq y \leq 0.8\%$) ($\lambda_{\text{ex}} = 407 \text{ nm}$).

spectra in Figure 3. Therefore, the PL properties of the series $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Zn}^{2+}$ and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Al}^{3+}$ were further investigated.

Figures 5 and 6 present the series of PL spectra of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Zn}^{2+}$ and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, y\text{Al}^{3+}$ under 407 nm excitation, respectively. A little amount of Zn^{2+} and Al^{3+} codoping can facilitate the enhancement of luminescence intensity of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$. When codoping amount of Zn^{2+} is 0.6%, the luminescence intensity of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ can be enhanced to 1.59 times as Zn^{2+} free sample. On the same conditions, 0.6% Al^{3+} ions codoping can make 1.51 times luminescence intensity enhancement compared to Zn^{2+} free sample. The codoping amount of 0.6% is critical doping concentration of Zn^{2+} and Al^{3+} ions. When the codoping concentration y exceeded 0.6%, the PL intensity became decreasing; that was also caused by nonradiative

TABLE 1: The chromaticity coordinates for $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$ phosphors ($\lambda_{\text{ex}} = 407 \text{ nm}$).

Samples	The chromaticity coordinates	
	x	y
$\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$	0.616	0.383
$\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$	0.617	0.383
$\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$	0.617	0.382

energy transfer among Sm^{3+} ions. The corresponding quantum efficiencies of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$ and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$ were measured as 39.67 and 37.21 under 407 excitation, respectively. The values are higher than that of commercial red phosphor of $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ ($\text{QE} = 35\%$) under 317 nm excitation [22].

The chromaticity coordinates for $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$ phosphors with 407 nm excitation were simulated and listed in Table 1. With 0.6% Zn^{2+} or 0.6% Al^{3+} ions codoping, the chromaticity color coordinates of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ have hardly any movements, which are all in reddish-orange region.

4. Conclusion

The series of phosphors $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$ codoped with Zn^{2+} or Al^{3+} ions were prepared by solid state reaction and their luminescence properties were investigated. Codoping Zn^{2+} or Al^{3+} ions can enhance the emissions of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$ excited by 407 nm, but the effects are different. The introduction of Zn^{2+} ions can favor the charge balance in $\text{CaIn}_2\text{O}_4:\text{Sm}^{3+}$ to facilitate its photoluminescence, but Al^{3+} ions can effectively help energy transferred from CTB to characteristic transition of Sm^{3+} ions, utilizing more energy from host absorption to the photoluminescence of Sm^{3+} ions. All the chromaticity coordinates of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}$, $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$, and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$ are in reddish orange region and very close. The excellent luminescence properties of $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Zn}^{2+}$ and $\text{CaIn}_2\text{O}_4:0.6\%\text{Sm}^{3+}, 0.6\%\text{Al}^{3+}$ both present potential application value for WLEDs.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was supported by the Fundamental Research Funds for the Central Universities (GK201402015), National Natural Science Foundation of China (21302118), and Fundamental Doctoral Fund of Ministry of Education of China (20130202120015).

References

- [1] H. A. Höppe, “Recent developments in the field of inorganic phosphors,” *Angewandte Chemie—International Edition*, vol. 48, no. 20, pp. 3572–3582, 2009.
- [2] S. Neeraj, N. Kijima, and A. K. Cheetham, “Novel red phosphors for solid-state lighting: the system $\text{NaM}(\text{WO}_4)_{2-x}(\text{MoO}_4)_x$: Eu^{3+} ($\text{M}=\text{Gd}, \text{Y}, \text{Bi}$),” *Chemical Physics Letters*, vol. 387, no. 1–3, pp. 2–6, 2004.
- [3] T. Nishida, T. Ban, and N. Kobayashi, “High-color-rendering light sources consisting of a 350-nm ultraviolet light-emitting diode and three-basal-color phosphors,” *Applied Physics Letters*, vol. 82, no. 22, pp. 3817–3819, 2003.
- [4] J. S. Kim, P. E. Jeonny, J. C. Choi, H. L. Park, S. I. Mho, and G. C. Kim, “Warm-white-light emitting diode utilizing a single-phase full-color $\text{Ba}_3\text{MgSi}_2\text{O}_8:\text{Eu}^{2+}, \text{Mn}^{2+}$ phosphor,” *Applied Physics Letters*, vol. 84, no. 15, pp. 2931–2933, 2004.
- [5] L. Zhang, Z. Lu, P. Han, L. Wang, and Q. Zhang, “Effective red compensation of $\text{Sr}_2\text{SiO}_4:\text{Dy}^{3+}$ phosphor by codoping Mn^{2+} ions and its energy transfer,” *Journal of Nanomaterials*, vol. 2012, Article ID 848274, 7 pages, 2012.
- [6] S. Nakamura and G. Fasol, *The Blue Laser Diodes: GaN Based Blue Light Emitters and Lasers*, Springer, Berlin, Germany, 1997.
- [7] F. Lei and B. Yan, “Hydrothermal synthesis and luminescence of $\text{CaMO}_4:\text{RE}^{3+}$ ($\text{M}=\text{W}, \text{Mo}$; $\text{RE}=\text{Eu}, \text{Tb}$) submicro-phosphors,” *Journal of Solid State Chemistry*, vol. 181, no. 4, pp. 855–862, 2008.
- [8] C. F. Guo, D. X. Huang, and Q. Su, “Methods to improve the fluorescence intensity of $\text{CaS}:\text{Eu}^{2+}$ red-emitting phosphor for white LED,” *Materials Science and Engineering B: Solid-State Materials for Advanced Technology*, vol. 130, no. 1–3, pp. 189–193, 2006.
- [9] Y. Q. Li, G. de With, and H. T. Hintzen, “The effect of replacement of Sr by Ca on the structural and luminescence properties of the red-emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ LED conversion phosphor,” *Journal of Solid State Chemistry*, vol. 181, no. 3, pp. 515–524, 2008.
- [10] J. S. Liao, L. B. Liu, H. Y. You, H. P. Huang, and W. X. You, “Hydrothermal preparation and luminescence property of $\text{MWO}_4:\text{Sm}^{3+}$ ($\text{M} = \text{Ca}, \text{Sr}, \text{Ba}$) red phosphors,” *Optik*, vol. 123, no. 10, pp. 901–905, 2012.
- [11] Y. Huang, W. Kai, Y. Cao et al., “Spectroscopic and structural studies of Sm^{2+} doped orthophosphate K Sr PO_4 crystal,” *Journal of Applied Physics*, vol. 103, no. 5, Article ID 053501, 2008.
- [12] Q. Wang, Z. Ci, G. Zhu et al., “Multicolor bright Ln^{3+} ($\text{Ln} = \text{Eu}, \text{Dy}, \text{Sm}$) activated tungstate phosphor for multifunctional applications,” *Optical Materials Express*, vol. 4, no. 1, pp. 142–154, 2014.
- [13] X. M. Liu, C. X. Li, Z. W. Quan, Z. Y. Cheng, and J. Lin, “Tunable luminescence properties of $\text{CaIn}_2\text{O}_4:\text{Eu}^{3+}$ phosphors,” *Journal of Physical Chemistry C*, vol. 111, no. 44, pp. 16601–16607, 2007.
- [14] X. M. Liu, R. Pang, Q. Li, and J. Lin, “Host-sensitized luminescence of $\text{Dy}^{3+}, \text{Pr}^{3+}, \text{Tb}^{3+}$ in polycrystalline CaIn_2O_4 for field emission displays,” *Journal of Solid State Chemistry*, vol. 180, no. 4, pp. 1421–1430, 2007.
- [15] F. S. Kao and T.-M. Chen, “A study on the luminescent properties of new green-emitting terbium-activated $\text{CaIn}_2\text{O}_4:\text{xTb}$ phosphors,” *Journal of Luminescence*, vol. 96, no. 2–4, pp. 261–267, 2002.
- [16] F. S. Kao and T. M. Chen, “A study on the luminescent properties of praseodymium-activated CaIn_2O_4 phosphors,” *Journal of Solid State Chemistry*, vol. 155, no. 2, pp. 441–446, 2000.
- [17] X. Yan, W. Li, and K. Sun, “A novel red emitting phosphor $\text{CaIn}_2\text{O}_4:\text{Eu}^{3+}, \text{Sm}^{3+}$ with a broadened near-ultraviolet absorption band for solid-state lighting,” *Materials Research Bulletin*, vol. 46, no. 1, pp. 87–91, 2011.
- [18] D. L. Dexter, “A theory of sensitized luminescence in solids,” *The Journal of Chemical Physics*, vol. 21, no. 5, pp. 836–850, 1953.
- [19] D. L. Dexter and J. H. Schulman, “Theory of concentration quenching in inorganic phosphors,” *The Journal of Chemical Physics*, vol. 22, no. 6, pp. 1063–1070, 1954.
- [20] G. Blasse, “Energy transfer in oxidic phosphors,” *Philips Research Report*, vol. 24, no. 2, pp. 131–144, 1969.
- [21] J. Gou, Y. H. Wang, and H. Z. Guo, “Energy transfer in Dy^{3+} and Al^{3+} co-doping ZnNb_2O_6 ,” *Journal of Physics: Conference Series*, vol. 152, no. 1, Article ID 012081, 6 pages, 2009.
- [22] Y. Huang, Y. Nakai, T. Tsuboi, and H. J. Seo, “The new red-emitting phosphor of oxyfluoride $\text{Ca}_2\text{RF}_4\text{PO}_4:\text{Eu}^{3+}$ ($\text{R}=\text{Gd}, \text{Y}$) for solid state lighting applications,” *Optics Express*, vol. 19, no. 7, pp. 6303–6311, 2011.