S Synthesis and luminescence properties of novel Eu$^{2+}$/3+, Ce$^{3+}$ ion single- and co-doped BaZn$_2$(PO$_4$)$_2$ phosphors for white-light applications

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A series of novel Eu$^{2+}$/3+, Ce$^{3+}$ ion single- and co-doped BaZn$_2$(PO$_4$)$_2$ samples were prepared via a high-temperature solid-state reaction. XRD powder diffraction results indicated that all of the products were pure phases. The photoluminescence properties of BaZn$_2$(PO$_4$)$_2$:Eu showed that Eu$^{2+}$ and Eu$^{3+}$ coexist in the system and Eu$^{3+}$ can be self-reduced to Eu$^{2+}$ in an air atmosphere. In addition, the strongest emission peak of Eu$^{3+}$ ions at 593 nm implied that Eu$^{3+}$ ions occupy the inversion symmetry lattice and also the site of Zn in BaZn$_2$(PO$_4$)$_2$. We used the theoretical method of bond energy to explain why the self-reduction of Eu$^{3+}$ to Eu$^{2+}$ can occur in the BaZn$_2$(PO$_4$)$_2$ system. The calculation results indicated that the bond energy change value $\Delta E_{\text{Eu}^{2+}-\text{O}^{-}}$ is smaller than $\Delta E_{\text{Eu}^{3+}-\text{O}^{-}}$, indicating that Eu$^{2+}$ ions are more likely to occupy the Zn site and more stable than Eu$^{3+}$ ions in BaZn$_2$(PO$_4$)$_2$. Furthermore, the energy transfer process between Ce$^{3+}$ and Eu$^{2+}$ ions in the photoluminescence spectrum and the decay lifetime were observed, and the energy transfer mechanism was determined to be a dipole–dipole interaction. In this work, by adjusting the ratio of Ce and Eu ions, the emission color can be changed from blue to white, implying that the phosphor can be used as a promising candidate in the manufacture of white LEDs.

1. Introduction

Rare-earth doped luminescent materials have wide applications in the fields of illumination, display, laser, anti-counterfeiting, fiber-optic communication and biomedicine, and they have become a hotspot in many interdisciplinary research studies. Among most rare-earth ions, Eu$^{3+}$ ions have been extensively studied. It is a typical red-emitting rare-earth ion with an electronic structure of [Xe]4f$^6$, and its emission spectrum is caused by an electronic transition from the excited state $^5$D$_0$ high-energy level to the $^7$F$_J$ ($J = 0, 1, 2 \ldots 6$) ground-state energy level in the 4f configuration. If the Eu$^{3+}$ ion is located at the strict inversion center, its $^5$D$_0 \rightarrow ^7$F$_1$ electronic transition is the strongest at around 590 nm, emitting orange-red light. When the Eu$^{3+}$ ion is deviated from the inversion center position, the $^5$D$_0 \rightarrow ^7$F$_2$ electric dipole transition in the emission spectrum is the strongest at about 612 nm with red light. In recent years, the reduction from Eu$^{3+}$ to Eu$^{2+}$ has been found to occur in the same crystal in an air atmosphere. For example, in aluminosilicates, aluminate, silicate, phosphate, the reduction from Eu$^{3+}$ to Eu$^{2+}$ have appeared. The Eu$^{2+}$ spectral position changes with the strength of the crystal field, and ultraviolet, blue, and red light are generated according to the degree of splitting. Ce$^{3+}$ is also an important luminescent ion, and its transition between 4f and 5d is the allowed electric dipole transition; hence, it has high excitation and emission peaks. The interaction of the exposed d-electrons with the crystal field broadens the excitation and emission of Ce$^{3+}$, and the emission of light can be adjusted from the near-ultraviolet to red region depending on the matrix. This property allows Ce$^{3+}$ ions to spectrally overlap with most common luminescent ions in a specific matrix, greatly increasing the probability and efficiency of energy transfer. When the Ce$^{3+}$ ion is in an excited state, it can transfer energy to the co-doped rare-earth ion by resonance according to the ion spacing, which is a commonly used and excellent sensitizer. Ce$^{3+}$ ions can be co-doped with many ions such as Ce$^{3+}$, Tb$^{3+}$/Mn$^{2+}$ in Ca$_{19}$Ce(PO$_4$)$_{14}$, CaSc$_2$O$_2$:Ce$^{3+}$, Yb$^{3+}$/LiYSiO$_4$:Ce$^{3+}$, Eu$^{3+}$/BaY$^{2+}$Si$_2$O$_7$:Ce$^{3+}$, Pr$^{3+}$/K$_2$Ba$_5$S$_5$O$_{12}$:Ce$^{3+}$, and Eu$^{2+}$ (ref. 24) to generate energy transfer behavior.

The bond energy theory is used to analyze and explain the priority occupancy for doping ions entering the crystal lattice. The change in bond energy is smaller as per the bond energy theory when the doping ions replace the cation sites in the crystal lattice, in which the easier the doping ions preferentially occupy. At present, this theory has been effectively used in the CaAl$_2$Si$_2$O$_6$:Eu$^{3+}$, Ca$_{10}$M(PO$_4$)$_3$: [M = Li, Na, K]:Eu$^{2+}$/Eu$^{3+}$, and Sr$_2$(BO$_3$)$_3$:F:Eu$^{3+}$ (ref. 26) samples.

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MZN\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} (M = Mg, Ca, Sr, Ba) is an important host with the advantages of low cost, high luminescence efficiency, low synthesis temperature and good thermal stability. Based on these characteristics, BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} has also become one of the hot topics of discussion. In the previous reports, the properties of BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} phosphors have been studied. For example, the photoluminescence properties of BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2}:Ce\textsuperscript{3+}, Tb\textsuperscript{3+}/Dy\textsuperscript{3+} (ref. 27 and 28) and red phosphor BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2}:Sm\textsuperscript{3+} (ref. 29) have been studied. However, the lattice occupancy and the self-reduction phenomenon of Eu ion doping in BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} lattice and the energy transfer behavior of Ce\textsuperscript{3+}, Eu\textsuperscript{2+} co-doping in BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} have not been discussed.

In this work, a series of Eu\textsuperscript{2+/3+} and Ce\textsuperscript{3+} single- and co-doped BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} products were synthesized via a high-temperature solid-state reaction. First, the self-reduction phenomenon was found from Eu\textsuperscript{3+} to Eu\textsuperscript{2+} in the BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} system. Next, we use the bond energy method to analyze the self-reduction reaction from Eu\textsuperscript{3+} to Eu\textsuperscript{2+} in the lattice position of Zn in BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2}. At the same time, we use this method to explain why Eu\textsuperscript{3+} can be self-reduced to Eu\textsuperscript{2+}. Finally, the photoluminescence properties and energy transfer mechanisms of Ce\textsuperscript{3+}-Eu\textsuperscript{2+} ion co-doped BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} are studied in detail. In addition, based on the energy transfer, the emission color can be adjusted from blue to white by adjusting the relative proportions of Ce and Eu ions.

2 Experimental

2.1 Preparation of phosphors

A series of Eu\textsuperscript{2+/3+}, Ce\textsuperscript{3+} ion single- and co-doped BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} phosphors were synthesized by a traditional high-temperature solid-state method in an air atmosphere. The raw materials selected include BaCO\textsubscript{3}, (NH\textsubscript{4})\textsubscript{2}HPO\textsubscript{4}, ZnO, CeO\textsubscript{2} and EuO. The exact amount of raw materials of each component was calculated, and the analytical balance was accurately and effectively weighed. The raw materials were thoroughly ground and mixed evenly in an agate mortar, and transferred to an alumina crucible of appropriate size. Then the mixtures were pre-sintered at 850 °C for 4 h, and further calcined at 1000 °C for 4 h. Finally, all the as-synthesized products were naturally cooled to room temperature and ground to a powder.

2.2 Characterization methods

The phase purity characterization of the phosphors was performed using an X-ray diffractometer. Excitation source information: 40 kV, 40 mA on a Bruker D8 Advance X-ray diffractometer with Cu K\textalpha{} (\(\lambda = 1.5418\) Å) radiation. The scanning mode is continuous, the scanning speed is 2° per minute, and the test range is 5–80°. The morphologies of the samples were characterized by scanning electron microscopy (SEM) on an instrument of JSM 6510 LV Electronics, Japan; the resolution is 3 nm. The spectrometer FLS980 was used to test the emission and excitation as well as decay curves of the samples. A 450 W xenon lamp was used as a steady-state light source in the test and a 60 W\(\mu\text{F}\) flash lamp was used as the decay curve test source.

3. Results and discussion

3.1 Phase analysis and crystal structure

Fig. 1 depicts the XRD patterns of Eu\textsuperscript{2+/3+}, Ce\textsuperscript{3+} ion single- and co-doped BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} phosphors. Compared with the standard card JCPDS\#16-0554, it can be seen that the diffraction peaks of the synthesized samples corresponded well to the standard card, and no other diffraction peaks appeared. Therefore, the prepared samples were all pure phases and no impurities were formed. This indicates that rare-earth ions enter the BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} lattice, and no other impurity phases are formed; hence, the doping of these ions does not cause any change in the lattice structure of BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2}. However, the XRD patterns of Eu\textsuperscript{2+/3+}, Ce\textsuperscript{3+} ion single- and co-doped BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} phosphors are light-shifted compared with the pure BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} compound. This result could be attributed to the larger ionic radii of Eu\textsuperscript{3+} \((r = 1.09\) Å and 1.101 Å for CN = 4 and 7, respectively) and Ce\textsuperscript{3+} \((r = 1.07\) Å for CN = 7) with respect to those of Ba\textsuperscript{2+} \((r = 1.38\) Å for CN = 7, respectively) and Zn\textsuperscript{2+} \((r = 0.60\) Å for CN = 4, respectively). Moreover, as the radius of the dopant ions increase, the lattice gets distorted, and hence, the position of the diffraction peak shifts slightly.

The unit cell of BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} is exhibited in Fig. 2. BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} belongs to a monoclinic crystal structure of space group P2\textsubscript{1}/c. The unit cell contains five kinds of cation coordination environments, namely Ba\textsuperscript{1}, Zn\textsuperscript{1}, Zn\textsuperscript{2}, P\textsuperscript{1} and P\textsuperscript{2}. Ba\textsuperscript{1} forms isolated BaO polyhedra, which has seven coordination sites with an asymmetric polyhedron surrounded by oxygen atoms. Both Zn\textsuperscript{1} and Zn\textsuperscript{2} are tetrahedrons connected to oxygen. At the same time, there are two environments of tetrahedrons, one with vertices connected to a polyhedron centered on Ba and the other with a co-edge. P\textsuperscript{1} and P\textsuperscript{2} are also two four-coordinated sites. The parameters of the unit cell are a = 8.598 Å, b = 9.761 Å, c = 9.159 Å, and V = 768.45 Å\textsuperscript{3}, respectively.

The SEM micrograph, EDS mapping images and elemental distribution of Eu/Ce doped in BaZn\textsubscript{2}(PO\textsubscript{4})\textsubscript{2} synthesized under...
ambient conditions are displayed in Fig. 3. According to the SEM image of the two samples, we can see that all the samples have a block structure with inconsistent size. According to the EDS scanning structure and elemental distribution image, the atomic distribution patterns of Ba, O, P, Zn, Eu or Ce can be obtained very clearly in the Eu- or Ce-doped BaZn$_2$(PO$_4$)$_2$ samples. These indicate that the Ce and Eu elements are indeed present in the BaZn$_2$(PO$_4$)$_2$ sample.

### 3.2 Photoluminescence properties of BaZn$_2$(PO$_4$)$_2$:Eu

The excitation and emission spectra of the undoped BaZn$_2$(PO$_4$)$_2$ sample are shown in Fig. 4. At an excitation wavelength of 240 nm, the emission spectrum consists of a broad peak at a maximum wavelength position of 345 nm in the wavelength range of 300–425 nm (Fig. 4a). In the excitation spectrum (Fig. 4b), the maximum wavelength position of the excitation spectrum is at 240 nm.

Fig. 5 displays the photoluminescence spectra of BaZn$_2$(PO$_4$)$_2$:Eu phosphors. It can be found that a series of sharp peaks with an emission spectrum between 550–750 nm are due to the $^5$D$_0$–$^7$F$_J$ ($J = 0, 1, 2, 3, 4$) transition of Eu$^{3+}$ upon the 258 nm excitation, whose maximum wavelength position belongs to the $^5$D$_0$–$^7$F$_1$ transition at 593 nm. By monitoring the emission at 593 nm, it was found that the excitation spectrum in the range of 200–550 nm consists of a broadband excitation with a central wavelength at 258 nm, which is attributable to the charge transition of O$^{2–}$–Eu$^{3+}$ and some sharp peaks can be ascribed to the characteristic excitation of Eu$^{3+}$ in Fig. 5(a). We know that when the Eu$^{3+}$ ion is in a position with a strict inversion center, it will be dominated by the allowable $^5$D$_0$–$^7$F$_1$ magnetic dipole transition, and the emission peak is around 590 nm. Therefore, it can be judged that in the BaZn$_2$(PO$_4$)$_2$:Eu sample we prepared, the Eu$^{3+}$ ion occupies the inversion symmetry position. According to the asymmetrical structure centered on the Ba atom, it is presumed that the Eu$^{3+}$ ion enters a symmetric tetrahedral structure centered on the Zn atom.

The spectrum of the phosphor BaZn$_2$(PO$_4$)$_2$:Eu at different excitation and monitoring wavelengths is shown in Fig. 5(b).
Upon monitoring the wavelength at 532 nm, it was found that the excitation spectrum of BaZn$_2$(PO$_4$)$_2$:Eu consists of a narrow band absorption ranging from 200 to 450 nm with the dominant absorption peak at 374 nm, which comes from the 4f/$^5$d transition of Eu$^{2+}$ ions. Under the excitation of 283 and 375 nm, BaZn$_2$(PO$_4$)$_2$:Eu phosphors exhibited broad emission bands in the range of 350–750 nm with a maximum at 532 nm, which originates from the 5d/$^4$f transitions of Eu$^{2+}$ ions. At the same time, the emission sharp peaks belonging to the 5D$_0$–7F$_1$ transition of Eu$^{3+}$ at 593 nm can also be clearly observed. Therefore, the existence of Eu$^{2+}$ was proved. From Fig. 5(a), it can be observed that Eu$^{2+}$ and Eu$^{3+}$ coexist in the system, indicating that the self-reduction process from Eu$^{3+}$ to Eu$^{2+}$ occurred in the BaZn$_2$(PO$_4$)$_2$ crystal. We also made a Gaussian fitting to the excitation spectrum monitored at 532 nm wavelength and the emission spectrum at 365 nm wavelength, as shown in Fig. 5(c and d). The center positions of the three subexcitation peaks obtained by Gaussian fitting are at 282, 344, and 375 nm, respectively. This is due to the splitting of the excitation peak broadband. Similarly, two sub-emission peaks of the emission spectrum are obtained with center positions at 500 and 544 nm. From this, we conclude that Eu$^{2+}$ ions occupy two sites in the BaZn$_2$(PO$_4$)$_2$ lattice.

In BaZn$_2$(PO$_4$)$_2$ crystals, there are five kinds of cationic sites that can be occupied by the dopant, namely Ba1, Zn1, Zn2, P1 and P2. From the photoluminescence spectrum, we know that the strongest position of the emission peak of Eu$^{3+}$ ions is at 593 nm, indicating that Eu$^{3+}$ ions are in the inversion symmetry position and occupy the position of Zn. We use the theoretical method of bond energy to explain the reduction of Eu$^{3+}$ to Eu$^{2+}$ in the air and the priority of Eu$^{2+}$ and Eu$^{3+}$ ions in the lattice position of Zn in the system. It can be used by the following expression:

$$E_{Zn^{2+}/Eu^{3+}+O^2-} = J \exp \left(\frac{d_0 - d_{M-O}}{0.37}\right) \left(\frac{V_N}{V_M}\right)$$

where $V_N$ is the valence state of Zn$^{2+}$ cations in the system and $V_M$ is the number of valence states of Eu$^{2+}$ and Eu$^{3+}$. For Eu$^{3+}$ ions taken as an example, if Eu$^{3+}$ occupies the Zn site, then $V_N/V_M = 2/3$; if the doping ion Eu$^{2+}$ is at the Zn site, then $V_N/V_M = 1/1$. This indicates that the valence state has some effect on the bond energy of the crystal. $J$ represents the intrinsic standard atomization energy and $d_0$ is equal to a constant for a given pair of atoms. The $J$ and $d_0$ of the compounds involved are listed in Table 1. $E_{Zn^{2+}/O^2-}$, $E_{Eu^{3+}/O^2-}$ and $E_{Eu^{2+}/O^2-}$ are

<table>
<thead>
<tr>
<th>Ions</th>
<th>$J$ (kcal mol$^{-1}$)</th>
<th>$d_0$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn$^{2+}$–O$^{2-}$</td>
<td>86.900</td>
<td>1.704</td>
</tr>
<tr>
<td>Eu$^{3+}$–O$^{2-}$</td>
<td>109.400</td>
<td>2.074</td>
</tr>
<tr>
<td>Eu$^{2+}$–O$^{2-}$</td>
<td>56.180</td>
<td>2.049</td>
</tr>
</tbody>
</table>
calculated and shown in Table 2. The variation of bond energy reflects the preferential occupancy of the dopant ions. Its calculation method is as follows:

\[ \Delta E_{Zn} = |E_{Eu^{3+}} - E_{Eu^{2+}}| \]  

(2)

where \( \Delta E_{Zn} \) is the variation of bond energy, that is, a change of bond energy caused when \( Eu^{3+} \) and \( Eu^{2+} \) ions enter the lattice to replace the Zn1 and Zn2 sites. The smaller the change in bond energy, the easier it is to be occupied by dopant ions. Here, if the bond energy change value \( \Delta E_{Zn} \) is smaller than \( \Delta E_{O} \), then the \( Eu^{2+} \) ion is more likely to occupy the Zn site than \( Eu^{3+} \), which also implies that \( Eu^{3+} \) can be reduced to \( Eu^{2+} \) under non-reducing condition.

In summary, we calculated that when \( Eu^{2+} \) and \( Eu^{3+} \) ions are into the \( BaZn_{2}(PO_{4})_{2} \) matrix, the bond energy change values of \( Eu^{2+} \) and \( Eu^{3+} \) ions at the Zn1 and Zn2 sites by using the theoretical method of bond energy. The bond energy change value \( \Delta E_{Zn} \) is smaller than \( \Delta E_{O} \), indicating that \( Eu^{3+} \) is more likely to occupy the Zn site than \( Eu^{2+} \), which also implies that \( Eu^{3+} \) can be self-reduced to \( Eu^{3+} \). All theoretical calculations are consistent with the PL spectrum phenomenon.

Based on the principle of charge compensation mechanism, \( Eu^{3+} \) replaces the site of \( Zn^{2+} \), the charge in the environment is unbalanced. In order to maintain the overall charge exhibiting electrical neutrality, the formation of the cationic vacancy defect \( V_{Zn} \) will generate two negative electrons to compensate for the cation vacancy defects induced by \( Eu_{Zn} \). Then form a dipole complex \( V_{Zn} \), where \( Eu_{Zn} \) represents an electron donor and \( Eu_{Zn} \) an electron acceptor. When the negative charge generated on \( V_{Zn} \) is transferred to \( Eu_{Zn} \), \( Eu^{2+} \) will be reduced to \( Eu^{3+} \):

\[ 2Eu^{3+} + 3Zn^{2+} \rightarrow V_{Zn}^{+} + 2Eu_{Zn}^{3+} \]

3.3 Photoluminescence properties of \( BaZn_{2}(PO_{4})_{2}:Ce, Eu \)

Fig. 6 depicts the excitation and emission spectra of different concentrations of \( Ce^{3+} \) doped in \( BaZn_{2}(PO_{4})_{2} \). For Fig. 6(a), under the monitoring of 336 nm, the excitation spectrum is in the range of 230–310 nm, and the strongest absorption of these excitation bands is about 287 nm, which is due to the transition of the \( Ce^{3+} \) ion from the ground state to crystal field splitting level of the 5d state. In general, the emission spectrum of \( Ce^{3+} \) ion sample has a dual characteristic due to the ground state \( ^{2}F_{5/2} \) and \( ^{2}F_{7/2} \) spin orbital splitting, which indicates that \( Ce^{3+} \) is successfully doped into \( BaZn_{2}(PO_{4})_{2} \). As shown in Fig. 6(b), the emission spectra have two broad bands centered at 334 and 410 nm in the range of 300–500 nm, which can be clearly observed under the excitation at 287 nm.

The excitation spectra of the \( BaZn_{2}(PO_{4})_{2}:x\% Ce \) sample monitored at 336, 356 and 410 nm are shown in Fig. 6(c–e). We can see that the photoluminescence intensity reaches the maximum when the doping concentration of \( Ce^{3+} \) is 0.5%. At the same time, we normalized the excitation spectra under these different monitoring wavelengths, as shown in Fig. 6(f–h). At the monitoring wavelength of 336 nm, the broadband center of the excitation spectrum was located at 286 nm; it is worth noting that when the monitoring wavelength is 356 nm, the central position of the excitation spectrum changes with different concentrations of \( Ce^{3+} \) doping, that is, the central position of the broad excitation bands are 290 and 305 nm, respectively. In addition, the excitation spectrum exhibited a red shift phenomenon when monitored at 410 nm which is due to the influence of the crystal field. \(^{31,32}\) By comparing the excitation spectra at different monitoring wavelengths in Fig. 6, it can
be seen that in addition to the difference in luminescence intensity, the peak shape and the dominated peak position also have significant differences.

The emission spectrum of the BaZn$_2$(PO$_4$)$_2$:4% Ce, $x$% Eu series sample at an excitation wavelength of 304 nm for Ce$^{3+}$ is shown in Fig. 7(a). There are two distinct broadband emission peaks in the range of 300–800 nm, which are the 5d–4f transitions corresponding to Ce$^{3+}$ and Eu$^{2+}$ at 428 and 609 nm, respectively. In the BaZn$_2$(PO$_4$)$_2$:4% Ce, $x$% Eu co-doped sample, not only the emission of Ce$^{3+}$ but also the emission of Eu$^{2+}$ was observed by the 304 nm characteristic excitation of Ce$^{3+}$. At the same time, it can be clearly seen that as the concentration of Eu ions increases, the luminescence intensity of Ce$^{3+}$ ions gradually decreases, and that of Eu$^{2+}$ ions gradually increases. This strongly proves that energy transfer occurs between Ce$^{3+}$ and Eu$^{2+}$. Fig. 7(b) is the excitation spectrum obtained under the monitoring of 609 nm. It shows that there are three strong broad bands in the range of 225–550 nm, and their central positions at 248, 303 and 376 nm belong to the charge transition of O$^{2-}$–Eu$^{3+}$, the f-d energy level transition of Ce$^{3+}$ and the 4f-5d transition of Eu$^{2+}$, respectively. Therefore, we found that under the monitoring of Eu$^{2+}$, the excitation spectrum exhibits the excitation peak of Ce$^{3+}$, which further proves the phenomenon of Ce$^{3+}$–Eu$^{2+}$ energy transfer.

### 3.4 Energy transfer mechanism

In order to further study the energy transfer process, we tested the lifetime of Ce$^{3+}$ ions under 320 nm excitation ($\lambda_{ex} = 302$ nm, $\lambda_{em} = 428$ nm) and Eu$^{2+}$ ions under the corresponding excitation and emission wavelengths, as shown in Fig. 7(c). The decay curves are better fitted by the second-order exponential decay. The formula is as follows:

$$I(t) = A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right)$$  \hspace{1cm} (3)

where $I(t)$ represents the luminescence intensity; $A_1$ and $A_2$ are the amplitude constants; $t$ is the decay time; and $\tau_1$ and $\tau_2$ are the exponential components of fast and slow decay times, respectively. The average decay time ($\tau^*$) is calculated using the following formula:

$$\tau^* = (A_1\tau_1^2 + A_2\tau_2^2)/(A_1\tau_1 + A_2\tau_2)$$  \hspace{1cm} (4)

According to eqn (3) and (4), the decay time of Ce$^{3+}$ in BaZn$_2$(PO$_4$)$_2$:4% Ce, $x$% Eu samples are approximately 1.5, 1.47, 1.42, 1.31 and 1.30 $\mu$s corresponding to $x = 3, 4, 6, 8, 10$ in Fig. 7(c). We can observe that as the concentration of Eu ions increases, the lifetime of Ce$^{3+}$ ions decreases, whereas the lifetime of Eu$^{2+}$ ions increases, which is in good agreement with the...
spectral characteristics of BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu. This also strongly indicates the energy transfer behavior between Ce$^{3+}$ and Eu$^{2+}$ ions.

Based on Dexter’s theory, the critical distance of energy transfer is defined as the distance at which the transition probability is equal to the probability of Ce$^{3+}$ radiation emission. The critical distance $R_c$ for energy transfer between Ce$^{3+}$ and Eu$^{2+}$ in BaZn$_2$(PO$_4$)$_2$ is discussed by the following formula:

$$R_c = 2 \left( \frac{3V}{4\pi X_c N} \right)^{1/3}$$

where $V$ represents the volume of the unit cell and $X_c$ stands for the critical concentration of the dopant, and $N$ is the number of available sites per unit cell. In the BaZn$_2$(PO$_4$)$_2$ crystal structure, the values of $V$, $X_c$ and $N$ are 768.45 Å$^3$, 0.1 and 4, respectively. The critical distance $R_c$ is calculated to be 15.426 Å by eqn (5).

We know that when the distance between two luminescence centers is less than the critical distance of 5 Å, the energy transfer between the two luminescence centers is carried out by the exchange interaction mechanism, otherwise it is through electric multipolar interactions. Therefore, it can be seen that energy transfer from Ce$^{3+}$ to Eu$^{2+}$ in BaZn$_2$(PO$_4$)$_2$ belongs to electrical multipole interaction. Based on Dexter’s multipole interaction energy transfer formula and Reisfeld’s approximation, the mechanism in the present system is applied through the following relationship:

$$\frac{I_{S0}}{I_S} = C^{n/3}$$

where $I_{S0}$ indicates the luminescence intensity of Ce$^{3+}$ ions when Eu$^{2+}$ ions are not doped; $I_S$ is equal to the luminescence intensity of Ce$^{3+}$ ions with the presence of Eu$^{2+}$ ions; and $C$ stands for the sum of the concentrations when Eu$^{2+}$ and Ce$^{3+}$ coexist. When the value of $n$ is 6, 8, or 10, it means dipole–dipole (d-d), dipole–quadrupole (d-q), and quadrupole–quadrupole (q-q) interactions, respectively. The $I_{S0}/I_S$–$C^{n/3}$ plots are exhibited in Fig. 8. Obviously, when $n = 6, 8$ and 10, the linear fitting $R^2$ values of $I_{S0}/I_S$–$C^{n/3}$ are 0.9920, 0.9826 and 0.9667, respectively, that is, when $n = 6$, linear behavior is the best. Therefore, the energy transfer of Ce$^{3+}$–Eu$^{2+}$ in this system follows the electric dipole–dipole interaction mechanism. The quantum efficiency was determined to be 24.58%, 29.12%,

Fig. 7 (a and b) The emission spectrum of a series of BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu (x = 3, 4, 6, 8, 10) samples excited at 304 nm and the excitation spectrum monitored at 428 nm, respectively. (c) decay lifetime of Ce$^{3+}$ in BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu; (d) variations of the decay lifetime for Eu$^{2+}$ with the increasing Eu ion concentration in BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu ($\lambda_{ex} = 376$ nm, $\lambda_{em} = 600$ nm).
24.16%, 32.52%, and 29.02% for BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu with x = 3, 4, 6, 8, 10, respectively.

The chromaticity calculation was performed based on the photoluminescence spectra of the BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu phosphor at 304 nm excitation, and the calculation results of the CIE coordinates are shown in Fig. 9. Detailed CIE chromaticity coordinates are listed in Table 3. In a series of samples of BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu, as the doping concentration of Eu ions is from 0.03 to 0.1, we can see that the CIE coordinates of the samples change from the blue region to the white region. It is worth noting that the CIE chromaticity coordinates of the BaZn$_2$(PO$_4$)$_2$:4% Ce, 8% Eu sample in the white light region (0.3195, 0.2959) is very close to the ideal white luminescence (0.33, 0.33). It is suggested that the BaZn$_2$(PO$_4$)$_2$:4% Ce, 8% Eu phosphor has suitable color coordinates as white phosphors in the field of lighting. The results show that the light emission of white phosphors can be achieved by appropriately adjusting the ratio of Ce/Eu ions.

4. Conclusions

A series of novel Eu$^{2+}$/Ce$^{3+}$ single- and co-doped BaZn$_2$(PO$_4$)$_2$ samples have been synthesized via a high-temperature solid-state reaction. It was confirmed by XRD powder diffraction that our target products are all pure phases. The self-reduction from Eu$^{3+}$ to Eu$^{2+}$ has been found in the BaZn$_2$(PO$_4$)$_2$ system. The photoluminescence spectra show that Eu$^{2+}$ and Eu$^{3+}$ ions coexist in the BaZn$_2$(PO$_4$) crystal. At the same time, the strongest emission peak of Eu$^{3+}$ ions belongs to the $^5D_0$–$^7F_1$ transition of Eu$^{3+}$ at 593 nm, which indicates that Eu$^{3+}$ ions occupy the inversion symmetry lattice and occupy the site of Zn in BaZn$_2$(PO$_4$). According to the bond energy method, the priority of Eu$^{2+}$ and Eu$^{3+}$ ions in the lattice position of Zn and the self-reduction of Eu$^{3+}$ to Eu$^{2+}$ were explained in BaZn$_2$(PO$_4$). The results indicate that the value $\Delta E^{zn}_{Eu^{2+}}$ is smaller than $\Delta E^{zn}_{Eu^{3+}}$, indicating that Eu$^{2+}$ is more likely to occupy the Zn site and is more stable than Eu$^{3+}$ in BaZn$_2$(PO$_4$), which also explains why Eu$^{3+}$ ion can reduce to Eu$^{2+}$ ion. For BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu phosphors, the energy transfer from Ce$^{3+}$ to Eu$^{2+}$ was deduced by excitation and emission spectra, which was further confirmed by the decrease in the decay lifetime of Ce$^{3+}$ as the concentration of Eu ions gradually increases. The energy transfer mechanism between Ce$^{3+}$ and Eu$^{2+}$ proved to be a dipole–dipole interaction. Moreover, the CIE chromaticity coordinates show that the emission color of BaZn$_2$(PO$_4$)$_2$:4% Ce, x% Eu phosphors can be changed from blue to white. In particular, the chromaticity coordinates (0.3195, 0.2959) of BaZn$_2$(PO$_4$)$_2$:4% Ce, 8% Eu are very close to the ideal white luminescence (0.33, 0.33), indicating that the phosphor has potential applications in white LEDs.

Conflicts of interest

There are no conflicts to declare.

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Notes and references