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1 Introduction

In recent years, white light-emitting diodes (WLED), which are considered as energy-saving light source, have attracted more and more attention owing to their long operational life time, environmentally friendly properties and stability.1-5 Currently, the white light is mainly produced via a combination of leaked blue emission from an InGaN chip and the broad green-yellow emission of yellow phosphor Y₃Al₅O₁₂:Ce³⁺ (YAG:Ce³⁺).⁶⁻⁸ However, this approach limits the application range to cool white light with poor color rendering and a correlated higher colour temperature of approximately 4500-8000 K.9,10 The innate deficiency in the red spectral region reduces the suitability for indoor illumination. It is therefore logical to supplement a red phosphor into this system to improve the color rendering. This idea has stimulated research on red phosphors activated by rare earth or transition metal ions.

Among the available red phosphors, Eu^{2+} or Ce^{3+} ions doped nitrides are the most widely known, such as $Sr_2Si_5N_{18}:Eu^{2+}$, CaAlSiN₃: Eu^{2+} and $M_2Si_5N_8:Ce^{3+}$ (M = Ca, Sr, Ba).¹¹⁻¹³ Eu^{2+} doped nitrides and oxides have the advantages of high quantum efficiency and good thermal stability. However, the preparation process and reaction conditions of nitrides phosphors are

Hydrothermal synthesis of narrow-band red emitting K₂NaAlF₆:Mn⁴⁺ phosphor for warm-white LED applications

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A series of Mn^{4+} activated aluminofluoride (K₂NaAlF₆) red phosphors were synthesized *via* a hydrothermal route. The structure, morphology and composition were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDX). The photoluminescence properties were investigated by using emission and excitation spectra, temperature dependent luminescence spectra and decay curves. The obtained K₂NaAlF₆:Mn⁴⁺ can emit red light peaking at 633 nm under 460 nm excitation. The critical quenching concentration of Mn⁴⁺ was about 1%. The changes in Mn⁴⁺ emissions based on different ratios of KF to NaF, reaction temperature and reaction time were investigated in detail. Concentration and thermal quenching mechanisms were elucidated systematically. The white light-emitting diodes (WLED) fabricated with the as-prepared phosphor exhibit a low color temperature (4310 K), higher color rendering index ($R_a = 78.7$) and luminous efficacy of 60.22 lm W⁻¹. The inherent advantage of K₂NaAlF₆:Mn⁴⁺ makes it a promising red phosphor for future WLED.

rigorous.¹⁴⁻¹⁶ These shortcomings limit the application in white LEDs. Compared with the rare earth ions doped nitrides red phosphor, tetravalent manganese ions (Mn⁴⁺) doped fluoride or oxide phosphors exhibit a series of obvious advantages.17,18 First of all, Mn⁴⁺ ions display the characteristics of narrow emission and high color purity, which overcome the defect of broad emission bands and serious photon reabsorption in Eu²⁺ doped nitrides phosphors.¹⁹ In addition, the low price of transition metals effectively reduces the producing cost of LEDs. It is another important advantage that the Mn4+ ions activated phosphors can be excited by blue light chip. At present, Mn⁴⁺ doped oxide phosphors have attracted much attention.²⁰⁻²² The Jin's team reported a class of Mn⁴⁺ doped SrGe₄O₉ red phosphors by conventional solid-state reaction.23 The Mn4+ can replace Ge⁴⁺ sites in the host lattice owing to the same ionic radius of Mn⁴⁺ and Ge⁴⁺. SrGe₄O₉:Mn⁴⁺ phosphors exhibit red emission under excitation of 276 nm and 430 nm. In general, the near ultraviolet absorption peaks of Mn⁴⁺ doped oxide phosphors are higher than those of blue light, this property also limits the use of blue light chip. Therefore, numerous researchers have devoted their effort to investigate Mn4+substituted fluoride phosphor containing AF_6^{2-} (A = Ti⁴⁺, Ge⁴⁺ Si⁴⁺, Sn⁴⁺, Zr⁴⁺) octahedral environment.^{24,25} The outer 3d³ electron configurated Mn4+ activated phosphor shows two intense broad absorption bands ranged from 300 to 500 nm, attributing to spin-allowed ${}^{4}A_{2g} \rightarrow {}^{4}T_{1g}$ and ${}^{4}A_{2g} \rightarrow {}^{4}T_{2g}$ transition.^{26,27} The red emission near 600–700 nm under blue light excitation originates from the spin-forbidden ${}^{2}E_{g} \rightarrow {}^{4}A_{2g}$

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transition.28 For example, Zhou and his co-authors synthesized an efficient red phosphor BaGeF₆:Mn⁴⁺ by hydrothermal method and obtained the optimized reaction conditions.²⁹ In addition, BaGeF₆:Mn⁴⁺ is favourable for decreasing correlated color temperature (CCT) in WLED devices. Nguyen's group reported a co-precipitation method to produce a class of Na₂-SiF₆:Mn⁴⁺ red phosphor using NaOH/NaMnO₄ as starting materials in SiF_6^{2-}/HF system.³⁰ The result displayed the relative luminescence intensity maintained to 92% at 423 K than that at room temperature. Recently, Zhu's group³¹ had successfully prepared novel red-emitting phosphors K₂-LiGaF₆:Mn⁴⁺ with excellent thermal stability and luminescent properties, it was proved to be a potential commercial phosphor used in warm white LED devices. Huang's group³² had synthesized Mn⁴⁺ doped K₂SiF₆ phosphors using a novel HF-free hydrothermal synthetic. The synthetic route was more environmental friendly and the reaction mechanism of K₂SiF₆:Mn⁴⁺ was discussed in detail. According to the previous studies, it is not difficult to find that Mn⁴⁺ doped oxide or fluoride phosphors can exhibit red emission and effectively improve the performance of LEDs. K₂NaAlF₆ is a common elpasolite material. The crystal structure of K₂NaAlF₆ shows that Al³⁺ is surrounded by six F^- ions. The ${\rm AlF_6}^{3-}$ octahedron environment is beneficial for the emission of Mn⁴⁺.³³ Furthermore, the ionic radius of Al³⁺ and Mn⁴⁺ are similar. Mn⁴⁺ ions may be achieved by replacing Al³⁺ after entering the crystal lattice. Thus, we believe that K₂NaAlF₆ can be used as a suitable matrix for luminescent materials.

In this paper, we report a kind of elpasolite structure red phosphor $K_2NaAlF_6:Mn^{4+}$. The crystal structure and luminescence properties are investigated. Al^{3+} ions can be substituted by Mn^{4+} ions because of the smaller ionic radius. Meanwhile, the influences of synthesis conditions, such as raw material, reaction time, temperature and Mn^{4+} concentration on emission intensity have been discussed carefully in details. The experiment results show that $K_2NaAlF_6:Mn^{4+}$ phosphor is a promising red phosphor for future WLED.

2 Experimental

2.1 Materials

All the chemical reagents in our experiment, including potassium fluoride (KF, >98%), sodium fluoride (NaF, >98%), aluminium fluoride (AlF₃, >99%), hydrofluoric acid solution (HF, 40 wt%), potassium permanganate (KMnO₄, >99.5%), potassium hydrogen difluoride (KHF₂, >99%) and hydrogen peroxide aqueous solution (H₂O₂, 30.0%), were supplied by the Sinopharm Chemical Reagent Co. Ltd. All chemical reagents were used as obtained without further purification.

2.2 Preparation

Red phosphor $K_2NaAlF_6:Mn^{4+}$ was prepared *via* a hydrothermal route with K_2MnF_6 as the Mn^{4+} source. The K_2MnF_6 crystals were prepared based on Bode's method.³⁴ In a typical synthesis, AlF_3 (0.2444 g) and K_2MnF_6 (0.0222 g) were added to the 20 mL 40 wt% HF solution in a 50 mL plastic breaker. The mixture was

fully dissolved by magnetically stirring. Subsequently, NaF (0.1260 g) and KF (0.3487 g) were added into 20 mL distilled water until completely dissolved. Finally, a mixture of the NaF and KF was put into the above solution. After vigorous stirring for 30 min, the mixture solution was transferred into a 50 mL Teflon-lined autoclave and heated at 180 °C for 6 h, then cooled naturally to room temperature. The yellow solid products were collected by centrifugation, washed several times with distilled water and ethanol. The as-prepared products were dried for 12 h at 60 °C. Finally, the K₂NaAlF₆:Mn⁴⁺ red phosphor sample was obtained. The synthesis diagram of the preparation process is revealed in Fig. 1.

2.3 Fabrication of LED devices

The WLED devices were fabricated by combining GaN chips (~460 nm) with the mixture of obtained red phosphors K₂-NaAlF₆:Mn⁴⁺ and yellow phosphor YAG:Ce³⁺. First, the phosphors were completely mixed with epoxy resin, and then the mixture was coated onto the superficies of the GaN chip. The device was packaged with epoxy resin and solidified at 140 °C for 12 h. The fabricated devices were used for subsequent testing.

2.4 Characterizations

The crystal structures of all samples were investigated using a RigakuD/max-RA X-ray diffractometer with Cu K α radiation (λ = 0.15418 nm) in the 2θ range from 10° to 90° . The corresponding surface morphology and composition of the samples were examined by a FEI XL-30 field emission scanning electron microscope (FESEM) equipped with an attached energy dispersive X-ray (EDX) spectrometer. Photo-luminescence (PL), photoluminescence excitation (PLE) and luminescence decay curves of samples were measured on a HITACHI F-7000 fluorescence spectrophotometer equipped with a 150 W Xe lamp as the excitation source, scanning at 1200 nm min⁻¹. The temperature dependent luminescence properties were examined using a JobinYvon fluoro Max-4 equipped with a 150 W xenon lamp as the excitation source. Quantum efficiency was also measured using a photoluminescence quantum efficiency measurement system (C9920-02, Hamamatsu Photonics K. K., Japan).



Fig. 1 Synthesis diagram of $K_2NaAlF_6:Mn^{4+}$ phosphors via a hydrothermal method.

3 Results and discussion

3.1 Phase structure and morphology analysis

The phase purity and crystallinity of the as-prepared K₂-NaAlF₆:Mn⁴⁺ samples were first characterized by XRD. Fig. 2(a) shows the XRD pattern of the K₂NaAlF₆:Mn⁴⁺ sample along with JCPDS card no. 22-1235 at the bottom. The diffraction peaks of the phosphors can be matched well with the standard pattern of pure K₂NaAlF₆. No extra peaks of impurity are detected in the pattern, indicating the doped Mn⁴⁺ ions do not change the crystal structure of K₂NaAlF₆. The K₂NaAlF₆ is crystallized in a cubic *Fm*3*m* space group with lattice parameter of a = b = c = 8.122 Å. Fig. 2(b) displays the crystal structure of the K₂NaAlF₆. Al³⁺ is coordinated with six F⁻ to form a regular AlF₆³⁻ octahedron. Mn⁴⁺ ions would prefer to replace Al³⁺ ions in octahedral sites. Because Mn⁴⁺ (0.53 Å, CN = 6) has highly close ionic radius with Al³⁺ (0.535 Å, CN = 6).

The morphology and composition of the as-prepared K_{2} -NaAlF₆:Mn⁴⁺ were characterized by FESEM and EDX analysis, respectively. As show in Fig. 3(a), it can be seen that the asprepared phosphor displays truncated octahedron morphology with smooth surface. A side length of truncated



Fig. 2 (a) XRD pattern of the as-synthesized K_2NaAlF_6 :Mn⁴⁺ samples. The standard card (PDF#22-1235) is included for reference. (b) Schematic illustration of K_2NaAlF_6 crystal structure.



Fig. 3 (a) SEM images (a) and EDX spectrum (b) of K₂NaAlF₆:3%Mn⁴⁺.

octahedron is about 1 μ m. In the corresponding EDX spectrum (Fig. 3(b)), the results exhibit that the phosphors are composed of K, Na, Al, F and Mn element, respectively. The result also verifies that Mn element has been indeed doped into the lattice to occupy the Al lattice site. The detected C and Au element in Fig. 3(b) is ascribed to the conducting resin and metal spraying. The peak of the Si results from the silicon wafer used during the measurement.

3.2 Luminescence properties of K₂NaAlF₆:Mn⁴⁺

To determine the luminescence behaviour of Mn^{4+} in K₂NaAlF₆, we choose the samples by hydrothermal treatment at 180 °C for 6 h as an example. Fig. 4(a) presents the typical excitation and emission spectra at room temperature. As the monitoring wavelength at 633 nm, the photoluminescence excitation spectrum of K₂NaAlF₆:Mn⁴⁺ could be recorded in the wavelength range of 300–550 nm. There are two excitation bands located in the near-UV and blue region. The shape and range of excitation spectrum are basically consistent with those reported in the literature.³⁵ The weak excitation peak at 363 nm can be ascribed to the spin-allowed ${}^{4}A_{2g} \rightarrow {}^{4}T_{1g}$ transition of Mn⁴⁺ ions in K₂NaAlF₆. The dominating excitation peak at 460 nm is due to the transition from ground state ${}^{4}A_{2g}$ to ${}^{4}T_{2g}$ of Mn⁴⁺ ions.



Fig. 4 (a) Photoluminescence excitation (left) and emission (right) spectra, (b) decay curve of the $K_2NaAlF_6:3\%Mn^{4+}$ examined at room temperature by monitoring wavelength at 633 nm with a 460 nm light excitation and (c) CIE chromaticity coordinate of $K_2NaAlF_6:3\%Mn^{4+}$. The inset photographs represent the $K_2NaAlF_6:3\%Mn^{4+}$ phosphor in the daylight and under lamp (460 nm) irradiation.

The results demonstrate the excitation of $K_2NaAlF_6:Mn^{4+}$ can be well matched with the GaN blue chip and the prepared phosphors have a potential application for LEDs. Under excitation at 460 nm, the emission spectrum has series of narrow-line emission peaks ranged from 580 to 660 nm, with the maximum peak at 633 nm. The red emission line is attributed to ${}^2E_g \rightarrow {}^4A_{2g}$ transition of Mn^{4+} . The fluorescence decay curve for ${}^2E_g \rightarrow {}^4A_{2g}$ of the Mn^{4+} ions in red phosphor $K_2NaAlF_6:3\%Mn^{4+}$ monitored at 633 nm with the excitation of 460 nm was measured at room temperature, as shown in Fig. 4(b). The decay curve can be well fitted to a single-exponential model by the following equation:

$$I_{(t)} = I_0 + A e^{(-t/\tau)}$$

where $I_{(t)}$ is the luminescence intensity of K₂NaAlF₆:3%Mn⁴⁺ at time *t*, *A* is constant, I_0 is the initial intensity and τ is the lifetime for exponential components. The fluorescence lifetime value is about 3.91 ms. Fig. 4(c) displays the CIE chromaticity diagram of K₂NaAlF₆:3%Mn⁴⁺. The K₂NaAlF₆:Mn⁴⁺ red phosphor has aquantum efficiency of 16%. The CIE chromaticity coordinates of as-prepared phosphor were calculated to be x = 0.6384, y =0.3534, which is very close to the standard values of National Television Standard Committee (NTSC) (x = 0.67, y = 0.33). Therefore, K₂NaAlF₆:3%Mn⁴⁺ can exhibit a high red purity. The inset photographs in Fig. 4(c) represent the K₂NaAlF₆:3%Mn⁴⁺ phosphor in the daylight and blue light illumination, respectively. One can see obvious red emission light under blue light radiation.

The ratio of reactants is an important parameter for the phase purity and luminous intensity. In order to acquire better luminescent properties of the phosphors, we investigated the influence of different molar ratio of KF to NaF on crystal structure and luminescence properties. Fig. 5(a) shows the XRD patterns of K₂NaAlF₆:Mn⁴⁺ phosphors synthesized with different molar ratio of KF to NaF (1 : 1, 2 : 1, 4 : 1, 8 : 1, 12 : 1 and 20 : 1). When the molar ratio of KF to NaF is 1 : 1, the major diffraction peaks are close to the standard card PDF#22-1235. The three main diffraction peaks correspond to the lattice plane [220], [222] and [400], respectively, and the diffraction

intensity is very close. However, a weak impurity peak also appears near the diffraction angle about 30.6° , which is accordance with the standard card no. 30-1144 (Na₅Al₃F₁₄). The result



Fig. 5 (a) XRD patterns and (b) emission spectra ($\lambda_{ex} = 460$ nm) of the K₂NaAlF₆:Mn⁴⁺ phosphors synthesized with different molar ratios of KF to NaF (KF : NaF = 1 : 1, 2 : 1, 4 : 1, 8 : 1, 12 : 1 and 20 : 1).

implies that a part of impurity Na5Al3F14 can be generated in case of insufficient potassium source. When the molar ratio of KF to NaF gradually rises to 2:1-20:1, all the diffraction peaks of as-prepared samples can be in agreement with the JCPDS card no. 22-1235. No other impurity phases, such as Na₅Al₃F₁₄ or Na₃AlF₆ are detected, indicating that the product is pure phase. Fig. 5(b) is the emission spectra of K₂NaAlF₆:Mn⁴⁺ prepared with different molar ratio of KF to NaF. It can be seen that all the PL spectra of K₂NaAlF₆:3%Mn⁴⁺ are almost identical except for the luminescence intensity. When molar ratio of KF to NaF is 1:1, the red emission intensity is weak. With increasing the mole ratio of KF to NaF from 2:1 to 12:1, the red emission can be enhanced, the red emission intensity of sample (KF : NaF = 12 : 1) is about 1.52 times higher than that of samples (KF : NaF = 2 : 1), suggesting that appropriate adding the ratio of KF to NaF into the reaction system may enhance the intensity of Mn⁴⁺ doped K₂NaAlF₆ phosphor. But further increasing the ratio of KF to NaF, a weakening trend of emission spectrum is observed, which might be due to excessive K⁺ exacerbated the charge imbalance when the tetravalent Mn⁴⁺ replaced the trivalent Al^{3+} .

In order to investigate the effect of the reaction temperature on the phase and photoluminescence properties of K₂NaAlF₆:-Mn⁴⁺ phosphors. A series of K₂NaAlF₆:Mn⁴⁺ samples were synthesized at different temperatures for 6 h. Fig. 6(a) presents the XRD patterns of the phosphors obtained at different reaction temperatures. It is obviously seen that the diffraction peaks of these phosphors agree well with the cubic phase K₂NaAlF₆ [space group: $Fm\bar{3}m$] (PDF#22-1235), without any impurity phase. The increasing of the reaction temperature did not cause the change of the crystal structure and phase purity. Fig. 6(b) displays a series of corresponding emission spectra of K2-NaAlF₆:Mn⁴⁺ prepared under the reaction temperatures from 25 °C to 180 °C. Noted that the emission spectra also share the similar shape. With increasing the reaction temperature from 25 °C to 100 °C, the emission intensity sharply increases. Improving the proper reaction temperature can be beneficial for Mn⁴⁺ into the lattice to substitute Al³⁺ sites. Further increasing reaction temperature, the luminescent intensity of the assynthesized K2NaAlF6:Mn4+ phosphor decreases obviously under 460 nm blue light excitation. The possible reason is that the Mn⁴⁺ is not stable at very high temperature.

In addition to the molar ratio of raw materials and reaction temperature, the influence of reaction time on the luminescence of $K_2NaAlF_6:Mn^{4+}$ was also discussed. Fig. 7(a) presents the XRD patterns of the products obtained by different hydrothermal reaction times. It demonstrates that all the diffraction peaks are consisted with the standard data (PDF#22-1235) of K_2NaAlF_6 with a cubic structure. The phase purity and crystal structure of samples exhibit no significant change with increasing reaction times. The emission spectra of K_2NaAlF_6 :- Mn^{4+} prepared at different reaction times are shown in Fig. 7(b). The $K_2NaAlF_6:Mn^{4+}$ phosphors all display sharp red emission peaks covering from 550 nm to 700 nm with a maximum at 633 nm. It is clear that the emission intensity of as-prepared sample at 12 h is stronger than that of 6 h. As the reaction time further increases, the emission intensity of the



Fig. 6 (a) XRD patterns and (b) emission spectra ($\lambda_{ex} = 460$ nm) of the K₂NaAlF₆:Mn⁴⁺ samples synthesized at different reaction temperatures.

 K_2 NaAlF₆:Mn⁴⁺ decreases. The phenomenon of emission intensity dropped with prolonging reaction time from 12 h to 36 h may be due to the Mn⁴⁺ ions in the phosphors tend to instability in a long period time.³⁶ Therefore, fluorescence quenching results in lower luminous intensity.

The next part mainly concerns the influence of optical properties and structure for K₂NaAlF₆:Mn⁴⁺ prepared using various Mn⁴⁺ ions contents. As shown in Fig. 8(a), the XRD patterns of the obtained K_2 NaAlF₆:xMn⁴⁺ (x = 0.5%, 1%, 3%, 5% and 7%) phosphors are collected to verify the phase purity. All the characteristic diffraction peaks are in good agreement with the corresponding standard card data of K₂NaAlF₆ (PDF#22-1235). The results show that the Mn⁴⁺ ions enter the lattice of K₂NaAlF₆ without altering the crystal structure. The high diffraction intensities indicate that the phosphors have good crystallinity. Fig. 8(b) shows the emission spectra of K₂-NaAlF₆:Mn⁴⁺ with different Mn⁴⁺ doping concentrations. A series of emission peaks located at 611, 616, 625, 633 and 650 nm can be observed from the corresponding emission spectra of K₂NaAlF₆:Mn⁴⁺ under 460 nm blue light excitation. With increasing the concentration of Mn⁴⁺ ions, the emission intensity of as-prepared phosphor increases. When the manganese content reaches 1%, the sample obtains the strongest emission intensity. When further increasing Mn4+ ions concentration beyond 1%, the emission intensities of K2-NaAlF₆:Mn⁴⁺ have an obvious decreasing trend, which might be related to concentration quenching effect. Therefore, the



Fig. 7 (a) XRD patterns and (b) emission spectra ($\lambda_{ex} = 460$ nm) of the K₂NaAlF₆:Mn⁴⁺ samples synthesized at different reaction times.

optimum Mn^{4+} ions concentration in K_2NaAlF_6 host should be 1%, indicating that 1% is the quenching concentration in K_2 -NaAlF₆:Mn⁴⁺ phosphor. The phenomenon of the dropped emission intensity can be attributed to the occurrence of energy transfer within the adjacent Mn⁴⁺, which is finally end by a kill centre. Evidently, the energy transfer mechanism is not caused

by radiation re-absorption. Because there is no overlap between PLE and PL spectra of $K_2NaAlF_6:xMn^{4+}$. The exchange interaction or the dipole–dipole interaction may be responsible for the quenching. To clarify the point, the critical distance (R_c) was calculated with the following equation:³⁷

$$R_{\rm c} \approx 2 \times \left(\frac{3V}{4\pi x_{\rm c} N}\right)^{\frac{1}{3}}$$

where *V* is the volume of unit cell, x_c means the critical concentration. *N* is the number of the central cations in the unit cell. For K₂NaAlF₆:Mn⁴⁺, *V* = 534.99 Å, $x_c = 0.01$ and N = 4. Therefore, the critical distance of R_c is calculated to be 14.735 Å, which is larger than the typical critical distance (5 Å), so the possibility of exchange interaction is eliminated. The concentration quenching is related to multipolar energy transfer mechanism. According to the Dexter theory, the type of interaction between Mn⁴⁺ ions can be determined by the equation³⁸ as follows:

$$\frac{I}{x} = K \left[1 + \beta(x) \frac{\theta}{3} \right]^{-1}$$

where *I* is the emission intensity at activator concentration *x*, *K* and β are constants, the value of $\theta = 6$, 8, 10 represents the electric multipole index corresponding to the dipole–dipole (d–d), dipole–quadrupole (d–q) and quadrupole–quadrupole (q–q) interaction. The above equation can be predigested to

$$\log\left(\frac{I}{x}\right) = -\frac{\theta}{3}\log x + A$$

Fig. 8(c) shows the dependence of $\log(I/x)$ on $\log(x)$ with a slope of $(-\theta/3)$. A relative linear fitted can be obtained and the result of the slope is about 1.3. The value of θ is calculated approximately 6. Therefore, the mechanism of the concentration quenching of Mn⁴⁺ is d–d interaction in K₂NaAlF₆ host.

3.3 Temperature stability properties

The thermal stability of the phosphors is frequently used as an important parameter in LED applications. In order to investigate the influence of temperature on the luminescence of



Fig. 8 (a) XRD patterns, (b) emission spectra ($\lambda_{ex} = 460 \text{ nm}$) of the as-synthesized K₂NaAlF₆:xMn⁴⁺ (x = 0.5%, 1%, 3%, 5% and 7%), the inset photograph represents emission intensity of Mn⁴⁺ as a function of Mn⁴⁺ doping concentration, and (c) the relation plot of log(*I*/*x*) on log(*x*) of Mn⁴⁺ doping concentration *x*.

 $K_2NaAlF_6:Mn^{4+}$ phosphor, a series of emission spectra for $K_2-NaAlF_6:Mn^{4+}$ in the temperature range of 98–498 K was shown in Fig. 9(a). All the emission peaks are in same shape. As an increase of temperature, the positions of the emission peak have no obvious shift with the strongest emission peak at ~633 nm. The luminous intensity displays a decreasing trend with an increase in temperature from 98 K to 498 K. Fig. 9(b) displays the relative intensity trend at 633 nm of $K_2NaAlF_6:-Mn^{4+}$. Increasing the temperature, the luminous intensity decreases gradually. Upon heating the phosphor to 448 K, the emission intensity remains approximately 65% of the emission intensity at 298 K. The phenomenon of thermal quenching is attributed to the non-radiative transition, which can be fitted by the following equation:³⁹

$$I_T = \frac{I_0}{1 + c \times \exp\left(-\frac{\Delta E}{kT}\right)}$$

where I_T is the intensity at temperature T, I_0 is the initial intensity, *c* is the frequency factor, ΔE is the activation energy of the thermal quenching and K is the Boltzmann constant (8.629 $\times 10^{-5}$ eV K⁻¹). According to the above equation, the activation energy of the as-prepared K₂NaAlF₆:Mn⁴⁺ red phosphor is 0.3 eV, suggesting the excellent thermal stability. The phenomenon of thermal quenching can be illustrated by configuration coordinate diagram (Fig. 9(c)). Under near UV and blue light excitation, the electrons are excited to the excited state, from ${}^{4}A_{2g}$ to ${}^{4}T_{1g}$ and ${}^{4}T_{2g}$ levels of Mn⁴⁺ ions in K₂NaAlF₆ hosts. Subsequently, the electrons of ${}^{2}E_{g}$ level transit to the ground state ⁴A_{2g} level by radiative transition, which brings out the red emission of Mn⁴⁺ ions. As the temperature increases, a part of the electrons absorbing activation energy ΔE go back to the ground state *via* the crossover point of the states of ${}^{4}T_{2g}$ and ${}^{4}A_{2g}$, resulting in non-radiation transition to ground state ${}^{4}A_{2g}$ and the formation of thermal quenching.

3.4 Luminescence performance of WLEDs

To validate the availability of K₂NaAlF₆:Mn⁴⁺ for the blue-based white LED application, the synthesized red phosphor



Fig. 10 (a) Electroluminescence spectra of blue chip, LED assembling the blue light chip – YAG:Ce³⁺, and YAG:Ce³⁺–K₂NaAlF₆:Mn⁴⁺ under 20 mA current excitation. (b) The corresponding CIE chromaticity coordinates of LED devices.

 $K_2NaAlF_6:Mn^{4+}$ was mixed with the YAG:Ce³⁺ and the mixture coupled with a 460 nm blue LED to fabricate a WLED. Fig. 10(a) displays the electroluminescence spectra of the blue light chip, LED composed of blue light chip and YAG:Ce³⁺, YAG:Ce³⁺–



Fig. 9 (a) Emission spectra of K₂NaAlF₆:Mn⁴⁺ upon excitation of 460 nm, (b) temperature dependence of the relative intensity of ${}^{2}E_{g} \rightarrow {}^{4}A_{2g}$ transition of Mn⁴⁺ in K₂NaAlF₆, and (c) configurational coordinate diagram for illustration the possible thermal quenching process of Mn⁴⁺ in the K₂NaAlF₆ host.

Table 1 Measured photometric and chromaticity for the LEDs

Sample	CIE coordinates (x, y)	CCT	R _a	Luminous efficiency
A D E	0.1460, 0.0359 0.3530, 0.3956 0.3759, 0.4075	4882 K 4310 K	70.9 78.7	24.52 lm W ⁻¹ 108.23 lm W ⁻¹ 60.22 lm W ⁻¹

K₂NaAlF₆:Mn⁴⁺ under 20 mA current excitation. The emission peak of blue light chip is \sim 460 nm, and it overlaps with the excitation spectrum of red phosphor K₂NaAlF₆:Mn⁴⁺. Compared with the LED prepared by combining with YAG:Ce³⁺, the prepared LEDs that blends YAG:Ce³⁺ and K₂NaAlF₆:Mn⁴⁺ shows a warm white light property by the naked eye. The CIE chromaticity diagram and the object photograph of the LEDsdevices are exhibited in Fig. 10(b). The related photoelectric parameters such as correlated color temperature (CCT), color rendering index (CRI) and luminous efficacy of these LEDs, are listed in Table 1. The corresponding CIE coordinates of LEDs shift from cool white light (0.3530, 0.3956) to warm white light (0.3759, 0.4075). The CCT of the WLEDs is dropped from 4882 K to 4310 K, and the CRI improves from 70.9 to 78.7. However, the luminous efficiency of the LEDs decreases from 108.23 lm W⁻¹ to 60.22 lm W^{-1} . These results indicate that the red phosphors can enhance LED performance and have potential applications in the field of indoor lighting.

4 Conclusions

In summary, a class of red phosphor K₂NaAlF₆:Mn⁴⁺ was prepared by hydrothermal method, and its crystal structure, morphology, composition, optical properties were characterized. Under excitation of blue light, K₂NaAlF₆:Mn⁴⁺ can give a red emission located at 633 nm ascribed to the transition of ${}^{2}E_{g} \rightarrow {}^{4}A_{2g}$. The influence of synthesis conditions, including the ratio of reaction materials, reaction temperatures and times, the concentrations of Mn⁴⁺ ions, on the crystal structure and optical properties of the K₂NaAlF₆:Mn⁴⁺ had been discussed carefully. Moreover, the critical distance between adjacent Mn⁴⁺ in the K₂NaAlF₆ host was calculated. The concentration quenching phenomenon appearing in the K₂NaAlF₆:Mn⁴⁺ is attributed to dipole-dipole interaction. The temperature dependent emission intensity shows that K₂NaAlF₆:Mn⁴⁺ has excellent thermal stability and is suitable for the working temperature of LEDs. Furthermore, the warm white LED is fabricated by coupling the 460 nm blue chip with a mixture of yellow (YAG:Ce³⁺) and red (K₂NaAlF₆:Mn⁴⁺) phosphor, which has lower color temperature (4310 K), higher color rendering index ($R_a = 78.7$) and luminous efficacy of 60.22 lm W⁻¹. Therefore, K₂NaAlF₆:Mn⁴⁺ is a promising red phosphor for warm white LEDs.

Conflicts of interest

There are no conflicts to declare.

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