Appropriate green phosphor of SrSi$_2$O$_2$N$_2$:Eu$^{2+}$,Mn$^{2+}$ for AC LEDs

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Abstract: An AC (altering current) LED exhibited the advantages of a low drive current, low static electricity, lack of need for a rectifier, and high extraction efficiency. The input operating voltage of an AC LED is around 80 V, and its operating frequency is 120 Hz or less. When the voltage is converted, a time gap of 1/120 s (10 ms), called dead time, is generated. This time gap is closely related to the scintillation phenomenon. Therefore, AC LEDs that have a phosphor composition, whose half-life composition can compensate for dead time that is generated during the voltage conversion, are sought to solve the problem of scintillation. The object of this work is to provide a phosphor SrSi$_2$O$_2$N$_2$:Eu$^{2+}$,Mn$^{2+}$ for AC LEDs, in which the dead time that is generated during the voltage conversion is compensated for by the half-life of the phosphor.

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References and links


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15. R. S. Liu, Y. H. Liu, and N. C. Bagkar, “Enhanced luminescence of SrSi$_2$O$_2$N$_2$:Eu$^{2+}$ phosphors by codoping with Ce$^{3+}$, Mn$^{2+}$, and Dy$^{3+}$ ions,” Appl. Phys. Lett. 91(6), 061119 (2007).


1. Introduction

Next-generation solid state lighting is based on white light-emitting diodes (WLEDs). They have attracted increasing attention because of their high brightness and light extraction efficiency, long lifetime, various sizes for produce, and environmental friendliness. In 2009, the journal, Nature, claimed that bulb technology was due for a change [1]. To protect the environment by saving energy and reducing carbon dioxide emissions, light-emitting diodes are the strongest candidate. WLEDs are widely used as backlights in electronic devices or displays, and they are expected to replace traditional fluorescent lamps for general lighting purposes because their efficiency and color rendering properties are significantly better. The most common white LED is composed of a yellow cerium doped yttrium aluminum garnet (Y$_3$Al$_5$O$_{12}$:Ce$^{3+}$) with a blue InGaN chip [2]. However, the white light that it produces poor color rendering because of color deficiency in the red regions. Nitride-based phosphors provide chemical and thermal stability, and most importantly, they provide long wavelength emission, which improves color rendering index (CRI). A higher color rendering index means greater similarity approach to sunlight, and greater effectiveness for display or illumination purposes. To overcome the poor CRI of traditional LED, green and red phosphors have been combined with blue LEDs [3–8]. The 5d orbitals of Eu$^{3+}$ or Ce$^{3+}$ in nitride compounds with highly covalent chemical bonds by nephelauxetic effect is significantly split into several levels under the strong crystal field. The crystal field splitting, which yields the downshift of the excited state of rare earth ions, resulting in phosphors that can be excited by blue light and whose emissions are red-shifted [9,10].

Very recently, rare-earth doped oxynitride or nitride compounds have been attracting increasing attention as photo luminescent materials because of their high brightness, low thermal quenching, thermal and chemical stability. The most commonly used orange-red phosphor is M$_5$Si$_3$N$_5$:Eu$^{2+}$ (M = Ca, Sr, Ba) [11,12]. SrSi$_2$O$_2$N$_2$:Eu$^{2+}$ is a commonly used yellow-green phosphor [13,14]. The luminescent properties of SrSi$_2$O$_2$N$_2$:Eu$^{2+}$ have been thoroughly investigated. To improve these photoluminescence properties, co-doping with different metal ions have been investigated, such as by Eu$^{3+}$ with Ce$^{3+}$, Dy$^{3+}$ and Mn$^{2+}$ [15]. Eu$^{3+}$ and Mn$^{2+}$ co-doped silicon-based oxynitride, with improved photoluminescence and energy transfer from Eu$^{3+}$ to Mn$^{2+}$ has been discussed elsewhere [16,17]. The purpose of this
work to elucidate the thermal luminescence mechanisms of SrSi$_2$O$_2$N$_2$:Eu$^{2+}$,Mn$^{2+}$ for exploitation in alternating current (AC) LED.

Typically, to operate light-emitting diodes steadily, they are supplied with power from an alternating current/direct current (AC/DC) converter, which converts a regular ac voltage to a low dc voltage for an LED driver. The drawback of this design is that the lifetime of the converter is around twenty thousand hours, but that of the LED device is around one million hours. Moreover, not only does the need for replacement of the converter increase cost, but also the conversion equipment generates heat, reducing the lifetime of the device and increasing power consumption. To solve the problem of operating DC LEDs with alternating current, alternating current light emitting diodes (AC LEDs) have been developed. A DC LED chip is cut into many pieces to concentrate power on it. Therefore, the transformer can be eliminated, reducing the amount of heat generated. The AC LED has the advantages of low drive current, low static electricity, the lack of a need for a rectifier, and high extraction efficiency. The input operating voltage of an AC LED is around 80V, and the frequency is 120 Hz or less [11]. When the voltage is converted, a time gap of 1/120 s (~10 ms), called dead time, is generated. This time gap is highly related to the scintillation phenomenon. Therefore, phosphor for use in AC LEDs, whose half-life can compensate for dead time that is generated during the voltage conversion is sought to solve the problem of scintillation. The object of this study is to develop phosphor SrSi$_2$O$_2$N$_2$:Eu$^{2+}$,Mn$^{2+}$ for AC LEDs, whose dead time that is generated during voltage conversion is compensated for by the half-life of the phosphor.

2. Experimental section

2.1 Materials and synthesis

Green phosphors, Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$, were prepared by gas-pressure sintering (GPS) and a solid-state reaction of SrCO$_3$ (Aldrich, 99.99%), Si$_3$N$_4$ (Aldrich, 99.9%), rare earth dopant Eu$_2$O$_3$ (Aldrich, 99.99%) and MnCO$_3$ (Cerac, 99.95%). The starting powder was ground in an agate mortar for 30 minutes to ensure homogeneity. The mixtures were placed in a boron nitride (BN) crucible and sintered at 1400°C for 1h under a pressure of 0.9MPa in the GPS furnace (FVPHP-R-5, FRET-25, Fujidempa Kogyo Co. Ltd.) with a graphite heater. After firing, the samples were cooled to room temperature. They were then ground again for subsequent use.

2.2 Characterization

The purity and composition of each phase were recorded on a PANalytical XPert’Pert PRO diffractometer in transmission mode with Cu Kα radiation ($\lambda = 1.5418$Å) at 45 kV and 40 mA. For phase identification, an average scan (0.03°/s) was performed. Data were collected in a 2θ range from 10° to 80° with intervals of 0.02°. Structural refinements were defined herein using a general structure analysis system (GSAS) refinement program. The photoluminescence excitation and emission spectra were obtained using a FluoroMax-3 and Fluoromax-P spectraophotometer at room temperature using a 150W Xe lamp and a Hamamatsu R928 photo-multiplier tube (PMT). Fluorescence decays were measured using an Edinburgh FLS920 spectrometer with a gated hydrogen arc lamp at room temperature. Two-dimensional and three-dimensional thermoluminescence spectra were recorded using an ROSB TL&OSL 3D spectrometer. The samples were irradiated under 254 nm for 1 minute, and the emission peak obtained during heating at 2°C/s. The devices were packaged using a 460 nm-chip with driving currents of 5-10 mA at 100 V and 60 Hz.

3. Results and discussion

3.1 XRD refinement and crystal parameter

Figure 1 presents XRD patterns of the series of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ co-doped Mn with different ratio form x = 0 to 0.08 samples are confirmed the phase purity. Nearly all of the
Diffraction peaks of the samples were consistent with those of SrSi$_2$O$_2$N$_2$ - ICSD # 172877 in the doping concentration range that were investigated in this study. The results indicate that the series of samples used in this research are structural and chemical SrSi$_2$O$_2$N$_2$. The crystal structure of SrSi$_2$O$_2$N$_2$ is triclinic (space group: P1). The Eu$^{2+}$ and Mn$^{2+}$ ions occupied the Sr site, and the coordination number was 7 [18]. The decrease in crystallinity of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04},$Mn$_x$ with increasing Mn$^{2+}$ dopant content was observed from the XRD patterns, which can be attributed to the variation of charges of dopants in the lattice. As shown in Fig. 1, the peaks of the XRD patterns shifted to a higher $2\theta$ angle as the Mn$^{2+}$ concentration increased, which revealing that Mn$^{2+}$ dopants were present in the host lattice.

![Fig. 1. XRD patterns of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04},$Mn$_x$ phosphors with various $x$.](image)

To confirm that the doped structure was consistent with the crystal structure SrSi$_2$O$_2$N$_2$, Rietveld refinement was performed as shown in Fig. 2. The Sr$_{0.96}Si_2O_2N_2:Eu_{0.04}$ sample was a single-phase compound and crystallized with a triclinic structure with a space group of P1. For Sr$_{0.96}Si_2O_2N_2:Eu_{0.04}$, the lattice constant are $a = 7.11067(1) \text{ Å}$, $b = 7.26255(0) \text{ Å}$, $c = 7.28997(3) \text{ Å}$, and cell volume = 363.485(2) Å. All of the observed peaks are satisfied the reflection condition and were consistent with the lattice constants and cell volumes. Mn$^{2+}$ was co-doped with Eu$^{2+}$ and Fig. 2 shows both the experimental and the calculated X-ray powder diffraction patterns thereof (with $x = 0$, 0.04 and 0.08) along with the corresponding difference with standard of the Rietveld refinement. The Sr$_{0.96}Si_2O_2N_2:Eu_{0.04},$Mn$_x$ samples were almost pure phase with highly crystallinity. Table 1 present the crystallographic data of the Mn-doped samples for the Mn occupation.
Fig. 2. Experimental (crosses), calculated (solid line) and difference (bottom) of Rietveld refinement of powder XRD patterns of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$, ($x = 0$, 0.04 and 0.08) samples.
Table 1. The crystallographic data of the sample for Mn occupation in Sr

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**MSi2O2N2** is a typical two-dimensional oxynitridosilicates. Silicon nitride ceramics contain more cross-linking which can be used to specify the degree of condensation. The degree of condensation in a network of SiN₄ tetrahedra can be easily evaluated the ratio of tetrahedral Si centers to bridging N atoms. The degree of condensation Si:N (κ) and the Si-N bond lengths in nitridosilicates are closely related to their behavior and structures. As the Si:N
ratio increases, the patterns of connectivity \([\text{SiN}_4]\) tetrahedra become more varied. The classical structures of two-dimensional nitridosilicates are MSiN\(_2\) (\(M = \text{Sr}, \text{Ba}\)), MSi\(_2\)O\(_2\)N\(_2\) (\(M = \text{Ca}, \text{Sr}, \text{Ba}\)), Ba\(_3\)Si\(_6\)O\(_9\)N\(_4\) and M\(_3\)Si\(_6\)O\(_{12}\)N\(_2\) (\(M = \text{Sr}, \text{Ba}\)). The MSi\(_2\)O\(_2\)N\(_2\) (\(M = \text{Ca}, \text{Sr}, \text{Ba}\)) structure has similar metal ion positions but different coordination numbers and silicate layers with analogous O/N ordering (Fig. 3(a)) [19]. The MSi\(_2\)O\(_2\)N\(_2\) group is built up by different ratio of \([\text{SiON}_3]\) and \(\text{Sr}^{2+}\) ions located in the tunnels along [100] [20]. The degree of condensation of this group is around 0.5. Figure 3(a) shows the layered silicate structure. The coordination number of Sr was seven, which included six oxygen and nitrogen. The co-doped activators, Eu\(^{2+}\) and Mn\(^{2+}\) were substituted for Sr. Figure 3(b) shows the changes of volume and cell parameters. The ionic radii of \(\text{Sr}^{2+}\) (VII), Eu\(^{2+}\) (VII) and Mn\(^{2+}\) (VII) are 1.21 Å, 1.20Å and 0.90 Å, respectively [21]. The contraction of the unit cells with increasing Mn\(^{2+}\) content in Sr\(_{0.96-x}\)Si\(_2\)O\(_2\)N\(_2\):Eu\(_{0.04}\),Mn\(_x\) proves that the smaller Mn\(^{2+}\) ions are substituted for the larger Sr\(^{2+}\) ions.

![Fig. 3. (a) Structure of SrSi\(_2\)O\(_2\)N\(_2\). (b) Changes of volume and cell parameters in Sr\(_{0.96}\).Si\(_2\)O\(_2\):Eu\(_{0.04}\),Mn\(_x\).](image)

3.2 Analysis of photoluminescence properties

The influence of Mn\(^{2+}\) concentration on the luminescence properties of Sr\(_{0.96-x}\)Si\(_2\)O\(_2\)N\(_2\):Eu\(_{0.04}\) was investigated by varying the Mn\(^{2+}\) concentration therein from 0 to 0.08. Figure 4 shows the excitation and emission spectra of the sample at room temperature. As can be seen in the photoluminescence spectrum, strong emission was observed at \(x = 0.02\) under excitation by 460 nm. Excitation at 460 nm gives a green broad band emission that is centered at 540 nm.
The emission band is associated with the $4f^6 5d^1$ to $4f^6 (5d-4f)$ transition of Eu$^{2+}$. Co-doping of the phosphors with Mn efficiently enhanced the luminescence intensity, and the emission intensity of each Mn co-doped phosphor exceeded that of than original Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$. In this study, the quantum efficiencies are also measured. The external quantum efficiency of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ is 65.7%. It is higher than Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ which is 60.8%. The excitation band is suitable by UV or blue chip to excite.

![Graph showing PLE and PL spectra](image)

Fig. 4. PLE and PL spectra of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ phosphors with various Mn contents. (PLE monitored at 540 nm and PL excited at 460 nm).

Analysis of the luminescence decay curves confirms the cause of the increase in intensity in the Mn co-doped Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ phosphors. Emission at 540 nm was detected upon excitation at 460 nm. Interestingly, the decay time of the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ phosphor is on the nanosecond scale (Fig. 5(a)). When Mn$^{2+}$ is added, the decay time scale is on the millisecond scale (Fig. 5(b)).

![Graph showing decay curves](image)

Fig. 5. Decay curves of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ phosphor at 540 nm (a) $x = 0$ and (b) $x = 0.02, 0.04, 0.06$ and 0.08.
Thermoluminescence is a form of luminescence that is exhibited by crystalline materials that are excited at higher energy, such as delivered X-rays or ultraviolet irradiation, at low temperature. Previously stored energy from electromagnetic radiation or other ionizing radiation is re-emitted as the material is heated. Figure 6 plots thermoluminescence glow curves of the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$,Mn$_x$ (x = 0 and 0.08) phosphors. The two-dimensional TL glow curves of the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$,Mn$_x$ materials with x = 0 have a higher temperature band located at 107 °C, and the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$,Mn$_x$ materials with x = 0.08 exhibit a band at a lower temperature of 98 °C. The glow curves depend on the concentration of Mn$^{2+}$. Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$,Mn$_x$ (x = 0.08) has shallow trap vacancies. The dominant temperature is around 60-100°C, at which the material is visibly and persistently luminescent materials. It is explained that the Mn co-doped sample could use as the green luminescence material for AC LED.

![Fig. 6. Thermoluminescence spectra of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$, Mn$_x$ phospors x = 0 (solid) and x = 0.08 (dash).](image)

To explain the thermoluminescence data, Fig. 7 plots the fitting curve. The rate of detrapping is expressed as by the following equation [21].

$$\frac{dn_h}{dt} = -B_h n_h n_c$$  \hspace{1cm} (1)

where the rate of the change of the electrons in the traps,

$$\frac{dn_c}{dt} = n_c (N - n) B - np$$  \hspace{1cm} (2)

where $n_v$ is the concentration of vacancies, and $n_c$ is the concentration of electrons in the conduction band. If the concentration of electrons in traps is $n$, the density of traps is $N$, and the probability of electron trapping is $B$, then the rate of excitation of electrons in traps can be calculated using Eq. (1).

Additionally, to determine the trapping parameters, the TL glow curve of the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$, Mn$_x$ phosphor was deconvoluted. The computer glow curve deconvolution (CGCD) method is used to calculate the kinetic parameters, which is popular analysis to obtain these parameters by following equation [22–24]:

$$I(T) = \frac{sn_v}{E} \exp \left( \frac{-E}{KT} \right) \times \left[ 1 + \frac{(b-1)s}{\beta} \int^{\infty}_{T_0} \exp \left( \frac{-E}{KT'} \right) dT' \right]^{-\frac{1}{b-1}}$$  \hspace{1cm} (3)
where $I(T)$ represents the TL intensity; $s$ is the frequency factor, and $n_0$ represents the number of trapped electrons with kinetic order $b$. The heating rate is $\beta$; $k$ is the Boltzmann constant, and $T_0$ is the initial absolute temperature. $T$ represents the absolute temperature of heating. The TL fitting curves of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}$ undoped and doped Mn$_x$ ($x = 0.08$) phosphors are shown in Fig. 7(a) and 7(b), respectively. It is obvious that the two different kinds of curves in $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}$ undoped and doped Mn$_x$ phosphor. Curve of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}$ has only one TL peak at about 107 °C. In the other hand, curve of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_{0.08}$ consists of three TL peaks at about 98, 168 and 214 °C. It can be seen that the intensity of fitted peak 1 is much stronger than that of fitted peak 2 and 3. The main peak (peak1) is from the contribution of Mn$^{2+}$ ions, which is illustrated the Mn$^{2+}$ ions form the swallowed defect. The defect could release the electron easier than the $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}$ compound. Table 2 presents data obtained by the deconvolution of the TL glow-curve.

![Fig. 7. Fitting curve of thermoluminescence spectra of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphors with (a) $x = 0$ and (b) $x = 0.08$.](image)

**Table 2. Optical Constants of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphors with $x = 0$ and $x = 0.08$.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Peak</th>
<th>$E$ (eV)</th>
<th>$S$ (s$^{-1}$)</th>
<th>$n_0$</th>
<th>$b$</th>
<th>$T_m$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 0$</td>
<td>–</td>
<td>0.888</td>
<td>11.4</td>
<td>$2.9 \times 10^4$</td>
<td>2</td>
<td>107</td>
</tr>
<tr>
<td>$x = 0.08$</td>
<td>Peak 1</td>
<td>0.801</td>
<td>10.3</td>
<td>$1.2 \times 10^4$</td>
<td>1.7</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Peak 2</td>
<td>0.874</td>
<td>8.3</td>
<td>$6.2 \times 10^2$</td>
<td>2</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Peak 3</td>
<td>1.206</td>
<td>13.3</td>
<td>$4.8 \times 10^2$</td>
<td>2</td>
<td>214</td>
</tr>
</tbody>
</table>
Figure 8 shows the three-dimensional (3D) TL emission spectra of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ ($x = 0$ and 0.08) phosphors. The Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ sample with $x = 0$ has a broad emission band that is attributed to the characteristic $4f^65d^1$ to $4f^7$ (5d-4f) transition of the Eu$^{2+}$ ion (Fig. 8(a)). In the Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ sample with $x = 0.08$, the transition of Mn was appeared to confirm assignment of each peak by the energy level of Mn$^{2+}$.

![Figure 8](image1.png)

**Fig. 8.** Three-dimensional thermoluminescence spectra of Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$Mn$_x$ phosphor (a) $x = 0$ and (b) $x = 0.08$.

From the three dimensional thermoluminescence spectra of samples could be used to predict the characteristic transitions [25]. The emission spectra in Fig. 8 consist of four bands at 490, 540, 562, and 574nm, which attributed to the 4f-5d transitions of four different Eu$^{2+}$ sites. The coordination number of Sr in SrSi$_2$O$_2$N$_2$ is seven. Each Sr atom surrounded by six oxygen atoms and a nitrogen atom. Figure 9 presents the four different types of sites for the Sr$^{2+}$ ions because of a distorted trigonal prismatic manner [26]. These four different crystallographic sites for Sr$^{2+}$ (or Eu$^{2+}$) is in line with the assignment of the observed shift of the color point when the concentration increasing from energy transfer in previous study [14]. Therefore, the thermoluminescence spectra could use to prove that there are four different sites of Sr$^{2+}$. From the Fig. 8, there is clear to obtain that the Mn-doped Sr$_{0.96-x}$Si$_2$O$_2$N$_2$:Eu$_{0.04}$ could enhance the intensity of 560 nm.
Figure 10 presents a possible electron trap mechanism, based on the 2D and 3D thermoluminescence spectra of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphor. The difference between the radii of $\text{Mn}^{2+}$ and $\text{Sr}^{2+}$ results in the easy formation of defects in this compound. The trap energy of $\text{Mn}^{2+}$ is about 0.80 eV (from Table 1), and thermoluminescence emission occurs around 98 °C. A comparison with the decay time of the $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphors reasonably to explain the emission intensity when the Mn ion is substituted by $\text{Sr}^{2+}$. The decay time of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphor is on the millisecond scale. As mentioned above, this is suitable for the AC LED. On this time scale, the flashing of the AC LED could be full in efficiently. Figure 11 displays a package of an AC LED with $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphor. It is pumped by a 460 nm-chip with 100V, 50mA and 60Hz and emits a yellow green color with $x = 0.2553$ and $y = 0.3152$. 

Fig. 9. The four coordination types of $\text{SrSi}_2\text{O}_2\text{N}_2$. 

Fig. 10. Thermoluminescence spectra scheme of $\text{Sr}_{0.96-x}\text{Si}_2\text{O}_2\text{N}_2: \text{Eu}_{0.04}, \text{Mn}_x$ phosphor, $x = 0.08$. 

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Fig. 11. Electroluminescence spectra of Sr_{0.96-x}Si_2O_2N_2:Eu_{0.04},Mn_x phosphor, x = 0.08 pumped by 460 nm-chip with 100V, 50mA and 60Hz.

4. Conclusions

This study explained why the Mn-doping of Sr_{0.96-x}Si_2O_2N_2:Eu_{0.04} phosphor increases its intensity of emission. Thermoluminescence glow curves are adopted to predict the characteristics. The trap parameters are calculated from the glow curve and reveal that the decay time is suitable for AC LEDs. Additionally, 3D TL emission spectra reveal the characteristic of difference of coordination environment in Sr^{2+}. This is the first time to develop a green phosphor for AC LEDs and prove the four different sites of Sr^{2+} through 3D TL emission spectra.

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