Photoluminescence and afterglow of deep red emitting SrSc$_2$O$_4$:Eu$^{2+}$

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This work deals with the photoluminescence (PL) properties of SrSc$_2$O$_4$:Eu$^{2+}$ and SrSc$_2$O$_4$:Eu$^{2+}$,Dy$^{3+}$. For this purpose a series of powder samples of SrSc$_2$O$_4$ with various concentrations of Eu$^{2+}$ and Dy$^{3+}$ was prepared. The samples were synthesised via a high temperature solid state route. Phase purity was investigated by conducting X-ray powder diffractometry. The PL properties of all prepared samples were elucidated by recording PL and PL excitation spectra. Furthermore, the temperature behaviour of the PL of SrSc$_2$O$_4$:Eu$^{2+}$ was investigated from 100 to 500 K. Diffuse reflectance spectra were recorded to investigate the optical properties of Eu$^{2+}$ doped SrSc$_2$O$_4$. Additionally, persistent luminescence of SrSc$_2$O$_4$:Eu$^{2+}$ and SrSc$_2$O$_4$:Eu$^{2+}$,Dy$^{3+}$ was investigated. To this end, PL lifetime measurements were conducted. SrSc$_2$O$_4$:Eu$^{2+}$ shows an emission band in the deep red spectral range. Moreover, it turned out that the red emission of SrSc$_2$O$_4$:Eu$^{2+}$ shows persistent luminescence too.

So far, not many red emitting luminescent materials on the basis of Eu$^{2+}$-doped oxides are known and even less showing persistent luminescence in the deep red spectral range. Most of the red or infrared emitting persistent phosphors are sulphide based compounds doped with lanthanide ions. Especially in the red region, this group of compounds provides a variety of different emission wavelengths. Unfortunately, such compounds usually are extremely sensitive against moisture and thus chemically unstable. Therefore, further efforts like encapsulation and surface modification are necessary to protect these compounds from degradation. A chemically more stable group of compounds are oxides. Usually, oxides are impervious against moisture. However, most oxides which show red persistent luminescence are doped with Cr$^{3+}$.

SrSc$_2$O$_4$ was firstly described and its structure solved by Carter and Feigelson in 1964. Later Gaume et al. reported on the spectroscopic properties of Yb$^{3+}$-doped SrSc$_2$O$_4$. To the best of our knowledge there is no report concerning the PL properties of Eu$^{2+}$ doped SrSc$_2$O$_4$. Therefore, a series of powder samples of SrSc$_2$O$_4$ with various contents of Eu$^{2+}$ and Dy$^{3+}$ was prepared. SrSc$_2$O$_4$ crystallizes in the orthorhombic crystal system with space group Pnam. In SrSc$_2$O$_4$ the Sr$^{2+}$ ions are surrounded by eight O$^{2-}$ ions. The ionic radius of 8-fold coordinated Sr$^{2+}$ is 1.26 Å. 8-Fold coordinated Eu$^{2+}$ and Dy$^{3+}$ ions exhibit ionic radii of 1.25 Å and 1.027 Å. Therefore, it is assumed that the Eu$^{2+}$ and Dy$^{3+}$ ions tend to occupy the Sr$^{2+}$ sites.

1. Introduction

Today, materials which show red photoluminescence (PL) or persistent luminescence are of great interest for various applications. Their uses as phosphors in light emitting diodes or as fluorescence probes in bio-imaging are only two potential fields of application for these materials. For this reason, many research groups are investigating different host compounds and various dopants to find new red emitting materials. Often, Eu$^{2+}$ is taken as a dopant to obtain red emission. Since the emission of Eu$^{2+}$ is due to interconfigurational d-f-transitions, the energy of the emission strongly depends on the host material. Therefore, the emission band of Eu$^{2+}$ can be shifted from the ultraviolet (UV) to deep red range of the electromagnetic spectrum by changing the chemical environment.

For instance, in a material providing a surrounding with little covalent character like BaAlF$_3$, the Eu$^{2+}$ emission occurs in the UV range at about 361 nm. With increasing covalent interaction the emission band of Eu$^{2+}$ can be located all over the visible spectrum. In CaAl$_2$O$_4$:Eu$^{2+}$ the emission band of Eu$^{2+}$ is located in the blue spectral range at about 436 nm. Green emission of Eu$^{2+}$ can be observed in oxides and oxy-nitrides like SrAl$_2$O$_4$:Eu$^{2+}$ ($\lambda_{em,max}$ = 512 nm) and β-SiAlON:Eu$^{2+}$ ($\lambda_{em,max}$ = 535 nm). Red 5d-4f-emission of Eu$^{2+}$ is commonly observed in nitrides and sulphides. For example, Sr$_2$Si$_3$N$_6$:Eu$^{2+}$ possesses an emission band at about 620 nm. Eu$^{2+}$ doped sulfides such as Ca$_2$Si$_2$Eu$_5$ or Sr$_2$Eu$_2$ show emission at about 650 and 615 nm, respectively.

2. Experimental

The SrSc$_2$O$_4$:Eu$^{2+}$ and SrSc$_2$O$_4$:Eu$^{2+}$,Dy$^{3+}$ samples as investigated in this work were synthesized by high temperature solid state reaction. Therefore, high purity educts SrCO$_3$ (Aldrich, 99.9%),
Sc$_2$O$_3$ (Treibacher Industrie AG, 99.99%), Eu$_2$O$_3$ (Treibacher Industrie AG, 99.99%), and Dy$_2$O$_3$ (Treibacher Industrie AG, 99.99%) were weighted in stoichiometric amounts and were thoroughly blended in acetone in an agate mortar. After drying at ambient temperatures, the obtained powder blends were calcined at 1400 °C for 12 h in Mo boats in a reducing hydrogen atmosphere (Westfalen, 99.999%). After calcination, red sinter bodies were obtained which were ground to a fine μ-powder.

Phase purity of the synthesized samples was investigated using X-ray powder diffractometry (XRD). XRD patterns were collected on a Rigaku MiniFlex II diffractometer working in Bragg–Brentano geometry using Cu K$_\alpha$ radiation. Step width and integration time were set to 0.02° and 1 s, respectively.

Particle size and morphology were investigated using scanning electron microscopy (SEM). Therefore, the scanning electron microscope Zeiss EVO MA10 equipped with a LaB$_6$-cathode was used. Pressure in the sample chamber was $5 \times 10^5$ Pa and acceleration voltage was 8 kV.

PL as well as PL excitation (PLE) spectra were recorded on an Edinburgh Instruments FSL900 spectrometer equipped with a Xe arc lamp (450 W) and a cooled (−20 °C) single-photon counting photomultiplier (Hamamatsu R2658P). Obtained PL spectra were corrected by applying a correction file obtained from a tungsten incandescent lamp certified by the National Physics Laboratory U.K.

Persistent luminescence decay (PLD) curves were recorded after exciting the samples for 15 min with an excitation wavelength of $\lambda_{ex} = 525$ nm. Absolute luminance and radiance was measured using the optical power meter 1830-C of Newport Corporation equipped with a Si-detector.

Temperature dependent PL measurements from 100 to 500 K were performed using the Oxford Instruments cryostat MicrostatN2. Liquid nitrogen was used as a cooling agent. Temperature stabilization time was 60 s and tolerance was set to ±3 K.

Diffuse reflectance (DR) spectra were recorded on an Edinburgh Instruments FS900 spectrometer equipped with a Xe arc lamp (450 W), a cooled (−20 °C) single-photon counting photomultiplier (Hamamatsu R928) as well as a Teflon-coated integration sphere. BaSO$_4$ (99.998%, Sigma-Aldrich) was used as a reflectance standard.

3. Results and discussion

The collected XRD patterns as well as the ICDD reference card of SrSc$_2$O$_4$ are depicted in Fig. 1 for comparison purposes. The diffractograms prove the formation of the orthorhombic SrSc$_2$O$_4$ phase without any impurity phases. In addition, with increasing Eu$^{2+}$ doping concentration no significant shift of the reflexes is observed. The diffractograms confirm the used synthesis route for the preparation of SrSc$_2$O$_4$:Eu$^{2+}$.

Morphology of the surface as well as particle size of the prepared samples were investigated by using SEM. Fig. 2 shows the obtained image of SrSc$_2$O$_4$. The prepared powders of SrSc$_2$O$_4$ are in micrometer range. Further, the particles are heavily cracked by crushing them in the agate mortar.

Reflectance behaviour of the doped and undoped SrSc$_2$O$_4$ powder samples was investigated by recording DR spectra. BaSO$_4$ was used as a reflectance standard. The obtained spectra are illustrated in Fig. 3. Undoped SrSc$_2$O$_4$ shows about 70% reflectance compared to BaSO$_4$, which is in line with the white to greyish body colour. This greying is ascribed to Mo impurities caused by the Mo foil used during the high temperature annealing. The Eu$^{2+}$ doped SrSc$_2$O$_4$ samples show strong absorption bands at about 320 and 475 nm. These bands are
assigned to transitions from the $^8S$ ([$\text{Xe}$]4f7) ground state to the 5d multiplet. With increasing Eu$^{2+}$ concentration this absorption increases and broadens towards the long wavelength range. Therefore, the body colour of SrSc$_2$O$_4$:Eu$^{2+}$ is shifted from light pink to red violet.

PL as well as PLE spectra of Sr$_{0.98}$Eu$_{0.02}$Sc$_2$O$_4$ are depicted in Fig. 4. The PLE spectrum was recorded monitoring the Eu$^{2+}$ emission at $\lambda_{em} = 720$ nm. The obtained PLE spectrum shows a broad band which consists of various unresolved bands. This band originates from the transition of the $^8S$ ground state to the excited states $^6P$ and $^8P$ ([$\text{Xe}$]4f$^6$5d$^1$). PL of SrSc$_2$O$_4$:Eu$^{2+}$ was measured upon excitation of $\lambda_{ex} = 525$ nm. The obtained spectrum shows a broad band in the deep red range of the visible spectrum. This emission band ranges from about 595 to 840 nm with a maximum at about 687 nm and a full width half maximum of about 103 nm (2098 cm$^{-1}$). Hence, the PL maximum of SrSc$_2$O$_4$:Eu$^{2+}$ is located in the first bio-imaging window.

The PLE spectra obtained from Sr$_{1-x}$Eu$_x$Sc$_2$O$_4$ with $x = 0.02$, 0.03, and 0.05 are depicted in Fig. 5. The PLE maximum shifts towards longer wavelengths with increasing Eu$^{2+}$ concentration. In addition to that, the PLE spectra broaden with increasing Eu$^{2+}$ concentration. The shift of the excitation maximum is mainly ascribed to a change in covalency. This is verified by calculating the centroid wavenumber of the excitation bands. The results are summarized in Table 1. With increasing Eu$^{2+}$ concentration the calculated energy of the centroid wavenumbers decrease. This observation reflects an increase in the covalency of the bonds of SrSc$_2$O$_4$:Eu$^{2+}$ and is attributed to the higher alkalinity of Eu$^{2+}$ compared to Sr$^{2+}$. To investigate the broadening of the excitation band in more detail, the crystal field splitting of the d-orbitals of Eu$^{2+}$ was calculated (see Table 1). With increasing Eu$^{2+}$ concentration crystal field splitting increases, too. Since Eu$^{2+}$ is slightly smaller than Sr$^{2+}$, the incorporation of Eu$^{2+}$ into SrSc$_2$O$_4$ leads to a smaller Sr site and thus to higher crystal field splitting of the d-orbitals.

PL spectra of Sr$_{1-x}$Eu$_x$Sc$_2$O$_4$ with $x = 0.001, 0.005, 0.010, 0.020, 0.030$, and 0.050 are illustrated in Fig. 6. The spectra were recorded using an excitation wavelength of $\lambda_{ex} = 525$ nm. No Eu$^{3+}$ emission was observed. Therefore, it is assumed that the concentration of Eu$^{2+}$ corresponds to the amount which was weighed out. With increasing Eu$^{2+}$ concentration the PL maximum shifts from 688 to 702 nm. In addition to that, with increasing doping concentration the PL intensity of Sr$_{1-x}$Eu$_x$Sc$_2$O$_4$ increases up to an Eu$^{2+}$ content of $x = 0.005$. At higher concentrations the PL intensity decreases due to concentration quenching (inset Fig. 6).

**Table 1** Excitation bands, crystal field splitting, and centroid shift of Sr$_{1-x}$Eu$_x$Sc$_2$O$_4$ with various Eu$^{2+}$ concentrations

<table>
<thead>
<tr>
<th>Sample (x)</th>
<th>$\lambda_{ex}$ range (nm)</th>
<th>Crystal field splitting (cm$^{-1}$)</th>
<th>Centroid wavenumber (cm$^{-1}$)</th>
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<tr>
<td>0.02</td>
<td>238–697</td>
<td>27 670</td>
<td>26 596</td>
</tr>
<tr>
<td>0.03</td>
<td>237–689</td>
<td>27 680</td>
<td>25 381</td>
</tr>
<tr>
<td>0.05</td>
<td>235–685</td>
<td>27 954</td>
<td>23 810</td>
</tr>
</tbody>
</table>
To investigate the mechanism of the energy transfer responsible for concentration quenching, van Uitert’s approach was applied:

\[ I(x) = k + A x^q \]  

(1)

Here, \( I \) is the intensity, \( k \) as well as \( A \) are constants, and \( x \) is the concentration of \( \text{Eu}^{2+} \). \( q = 3 \) corresponds to exchange interaction whereas \( q = 6, 8, \) and 10 corresponds to dipole–dipole, dipole–quadrupole, and quadrupole–quadrupole interaction, respectively. Fig. 7 depicts the experimental data and the fitting curves. The best fitting is obtained for \( q = 6 \) indicating that the mechanism of concentration quenching occurs via dipole–dipole interaction. This result is quite reasonable since the transitions of excitation and emission of \( \text{Eu}^{2+} \) are quantum mechanically allowed.

Furthermore, the critical distance \( R_c \) between the \( \text{Eu}^{2+} \) ions was calculated. \( R_c \) is defined as the distance at which the probability of energy transfer equals the probability of radiative transition. To estimate the critical distance \( R_c \) between \( \text{Eu}^{2+} \) ions in \( \text{SrSc}_2\text{O}_4: \text{Eu}^{2+} \) Dexter’s formula for dipole–dipole interaction can be used:

\[ R_c^6 = 0.63 \times 10^{25} \frac{Q_A}{E} \int F_S(E) F_A(E) dE \]  

(2)

In this equation \( Q_A \) is the absorption cross section of \( \text{Eu}^{2+} \) and \( E \) is the energy of maximum spectral overlap. \( \int F_S(E) F_A(E) dE \) represents the spectral overlap of the normalized PL (\( F_S(E) \)) and PLE (\( F_A(E) \)) spectrum of \( \text{Eu}^{2+} \). \( Q_A \) is \( 4.8 \times 10^{-16} \, \text{cm}^2 \). Here, \( f_d \) is the oscillator strength of the electronic transitions of \( \text{Eu}^{2+} \) and was taken as 0.02. The spectral overlap integral was calculated to be 0.03 eV\(^{-1}\). Plugging these values into eqn (2), \( R_c \) is calculated to be 20.3 Å.

In order to examine the temperature behaviour of the PL of \( \text{SrSc}_2\text{O}_4: \text{Eu}^{2+} \) PL spectra were recorded from 100 to 500 K. The resulting spectra are illustrated in Fig. 8. With increasing temperature the PL intensity gradually decreases. Moreover, the emission maximum shifts from 692 to 680 nm. Due to extending equilibrium distance between \( \text{Eu}^{2+} \) and its surrounding oxygen ligands with increasing temperature, crystal field splitting of the d-orbitals of \( \text{Eu}^{2+} \) decreases. As a consequence, the energetic distance between the d and f-orbitals increases and the emission maximum is shifted towards higher energy. The inset of Fig. 8 depicts the integrated PL intensity of the investigated sample. Fitting these data points with a Fermi–Dirac distribution yields the activation energy \( E_A \) for thermal quenching:

\[ I(T) = \frac{I_0}{1 + Be^{\frac{E_A}{K}}} \]  

(3)

In eqn (3) \( I(T) \) is the PL intensity at a certain temperature and \( I_0 \) is the PL intensity at zero kelvin. \( B \) is the frequency factor for thermal quenching, \( k = 8.617 \times 10^{-5} \, \text{eV K}^{-1} \) is the Boltzmann constant, and \( T \) is the temperature. Parameters \( I_0 \) and \( B \) were derived from the fitting function and are about 0.97 and 2945,
respectively. From this $E_A$ was calculated to be 0.25 eV. By applying $E_A$ to the following formula, $T_{1/2}$ can be calculated:

$$T_{1/2} = \frac{-E_A}{k \ln \left(\frac{1}{B}\right)}$$

(4)

$T_{1/2}$ is the temperature where PL intensity of a luminescent centre decreases to one-half of its maximal intensity. For the herein investigated Sr$_{0.999}$Eu$_{0.001}$Sc$_2$O$_4$ sample $T_{1/2}$ was calculated to be 357 K.

To investigate the persistent luminescence properties of Eu$^{2+}$ doped SrSc$_2$O$_4$, luminescent lifetime measurements were conducted. For that purpose, the investigated samples were charged for 15 min with an excitation wavelength of $\lambda_{ex} = 525$ nm. Fig. 9 shows the obtained PLD curves of Sr$_{1-x}$Eu$_x$Sc$_2$O$_4$ with $x = 0.001$, 0.005, and 0.010. The longest afterglow duration was found for Sr$_{0.999}$Eu$_{0.001}$Sc$_2$O$_4$. The corresponding PLD curve can be best fitted with the following equation:

$$I = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + A_3 e^{-t/\tau_3} + A_4 e^{-t/\tau_4}$$

(5)

here, $I$ is the PL intensity, $A_1$, $A_2$, $A_3$, and $A_4$ are fitting parameters, and $t$ is the time. $\tau_1$, $\tau_2$, $\tau_3$, and $\tau_4$ are the partial luminescence lifetimes of the exponential components. The average luminescence lifetime can be obtained using eqn (6):

$$\tau = \frac{A_1 \tau_1^2 + A_2 \tau_2^2 + A_3 \tau_3^2 + A_4 \tau_4^2}{A_1 \tau_1 + A_2 \tau_2 + A_3 \tau_3 + A_4 \tau_4}$$

(6)

Partial lifetimes and their corresponding emission fractions as well as the calculated average lifetime $\tau$ are summarized in Table 2. With increasing Eu$^{2+}$ content the PL lifetime of SrSc$_2$O$_4$:Eu$^{2+}$ decreases and the PLD curve becomes tri-exponential.

It is well known that additional incorporation of Dy$^{3+}$ into Eu$^{3+}$ doped materials can lead to long lasting persistent phosphors. In order to investigate the influence of Dy$^{3+}$ co-doping on the afterglow duration, additional luminescence lifetime measurements were performed on Sr$_{0.999}$Eu$_{0.001}$Dy$_{0.001}$Sc$_2$O$_4$ and Sr$_{0.999}$Eu$_{0.001}$Dy$_{0.005}$Sc$_2$O$_4$. Fig. 10 illustrates the PLD curves of co-doped SrSc$_2$O$_4$:Eu$^{2+}$,Dy$^{3+}$. Analogous to Eu$^{2+}$, with increasing Dy$^{3+}$ concentration the afterglow duration decreases. Another possibility to enhance the afterglow duration of SrSc$_2$O$_4$:Eu$^{2+}$ could be co-doping with Cr$^{3+}$. Further experiments should be performed to investigate the influence of Cr$^{3+}$ co-doping on the persistent luminescence properties of SrSc$_2$O$_4$:Eu$^{2+}$.

Fig. 11a depicts the luminance in dependence of the time. For comparison the solid line visualises the luminance value 0.32 mcd x m$^{-2}$ which is the minimum value commonly used for safety signage. The dashed line illustrates the limit of the sensitivity of the dark-adapted eye. For the Sr$_{0.999}$Eu$_{0.001}$Sc$_2$O$_4$ sample 0.32 mcd x m$^{-2}$ is reached after about 6 min. Absolute radiance is plotted in Fig. 11b. The absolute radiance values obtained after charging the sample for 15 min are considerably smaller compared to other deep red emitting persistent phosphors.

<p>| Table 2 | Persistent luminescence lifetimes $\tau$ as well as partial lifetimes $\tau_1$, $\tau_2$, $\tau_3$, and $\tau_4$ and the emission fractions $frac_1$, $frac_2$, $frac_3$, and $frac_4$ of Eu$^{2+}$ in Sr$_{1-x}$Eu$_x$Sc$_2$O$<em>4$ and Sr$</em>{1-x}$Eu$_x$Dy$_y$Sc$_2$O$_4$ |</p>
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<th>Sample $\tau$, y</th>
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<th>$frac_1$ (%)</th>
<th>$\tau_2$ (s)</th>
<th>$frac_2$ (%)</th>
<th>$\tau_3$ (s)</th>
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<td>1007.4</td>
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4. Conclusions

SrSc$_2$O$_4$:Eu$^{2+}$ powder samples were prepared and its PL properties were investigated, also time and temperature dependent. SrSc$_2$O$_4$:Eu$^{2+}$ shows a broad emission band in the deep red region of the spectrum with a maximum at about 687 nm. This deep red lying emission band is quite rare for oxidic host materials doped with Eu$^{2+}$. Further, no Eu$^{3+}$ emission was observed. The highest PL intensity was found for a Eu$^{2+}$ concentration of $x = 0.005$. At a higher Eu$^{2+}$ concentration the PL intensity decreases due to concentration quenching caused by energy transfer between Eu$^{2+}$ ions, likely resulting in energy migration to defect states. It turned out that in SrSc$_2$O$_4$:Eu$^{2+}$ energy transfer between Eu$^{2+}$ ions is of a resonance type and occurs via dipole–dipole interaction. The critical distance $R_c$ was calculated to be about 20.3 Å. Temperature dependent PL measurements revealed a $T_{1/2}$ value of 357 K. Additionally, it was found that SrSc$_2$O$_4$:Eu$^{2+}$ shows deep red persistent luminescence after charging it with an excitation wavelength of $\lambda_{ex} = 525$ nm. The longest afterglow duration was found for the sample Sr$_{0.999}$Eu$_{0.001}$Sc$_2$O$_4$. This sample reaches the value of 0.32 mcd $\times$ m$^{-2}$ after about 6 min what is considerably shorter than for comparable materials.$^{18}$ No increase in afterglow duration could be observed if SrSc$_2$O$_4$:Eu$^{2+}$ was additionally doped by Dy$^{3+}$. For this reason, it would be worth the effort to try to increase the afterglow duration by doping with additional ions like Cr$^{3+}$.

Acknowledgements

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References