Luminescence properties of Ce³⁺-doped NaPrP₄O₁₂ polyphosphate

T Shalapska¹, G Stryganyuk², A Gektin³, A Kotlov⁴,
P Demchenko⁵ and A Voloshinovskii⁵

¹ Institute of Physics, University of Tartu, 142 Riia str., 51014 Tartu, Estonia

² Helmholtz Centre for Environmental Research, 15 Permoserstr., 04318 Leipzig, Germany

³ Institute for Scintillation Materials, NAS of Ukraine, 60 Lenina ave., 6100 Kharkiv, Ukraine

⁴ HASYLAB at DESY, Notkestrasse 85, D-22607 Hamburg, Germany

⁵ Ivan Franko National University of Lviv, 8 Kyryla i Mefodiya str., 79005 Lviv, Ukraine

E-mail: tetiana.shalapska@ut.ee

Abstract

The studies on the crystal structure and luminescence properties have been performed for NaPr_{1-x}Ce_xP₄O₁₂ polyphosphate series. Excitation and emission spectra of Pr³⁺ and Ce³⁺ luminescence from NaPrP₄O₁₂:Ce³⁺ reveal clearly an efficient Pr³⁺ → Ce³⁺ energy transfer via migration over Pr³⁺-sub-lattice and a nonradiative resonant transfer to Ce³⁺ ion. Analysis on scintillation characteristics of NaPr_{1-x}Ce_xP₄O₁₂ series shows the highest light yield of 11 000 ± 1000 ph/MeV for NaPr_{0.99}Ce_{0.01}P₄O₁₂ proving the studied polyphosphates to be promising for their application in the detection of X-ray and gamma quanta.

1. Introduction

The studies of stoichiometric polyphosphate compounds doped with lanthanide ions are intensified considerably due to their numerous applications in modern light-emitting devices. The converters of VUV radiation, scintillator materials, and tunable UVV-UV laser sources rely on the lanthanide luminescence. The inorganic polyphosphates of MLnP₄O₁₂ composition (where M-alkali metal of Li, Na, K and Cs; Ln-lanthanide ions) have been extensively investigated in the past years due to their chemical stability upon a normal conditions and a reduced concentration quenching of the luminescence at the high concentration of Ln ions. In particular, NaGdP₄O₁₂:Tb³⁺ has been found to be more a preferable phosphor for plasma display panels (PDPs) than Zn₂SiO₄:Mn²⁺ [1]. LiGd(PO₃)₄:Eu³⁺ has been considered to be a potential red phosphor for mercury-free lamps and PDPs application [2]. In the case of CsGdP₄O₁₂:10.0at%Ce³⁺ a high light yield of the Ce³⁺ luminescence (24 400 photon/MeV) have been revealed [3]. However, Gd-containing inorganic polyphosphates reveal a slow component in a scintillator pulse that affects their luminescence properties [4, 5]. The introducing of the Ce³⁺ ions into the Pr³⁺-based compounds, one could avoid the presence of the slow component in scintillator pulse and obtain the higher light yield in such materials as a result of the energy transfer from Pr³⁺ to Ce³⁺ ions. This allows to increase significantly the efficiency of the Ce³⁺ 5d-4f luminescence [6, 7, 8].

The present work provides the investigations of the luminescence properties of the NaPrP₄O₁₂:Ce³⁺ polyphosphate considering the Pr³⁺-Ce³⁺ pair as a suitable candidate for the increasing of the scintillation efficiency, which can be useful for the converting of the ionizing radiation. The observations of spectral-kinetics characteristics of the NaPrP₄O₁₂:Ce³⁺ polyphosphate were performed upon the excitation with the high-energy VUV-UV quanta of the synchrotron radiation and X-rays. The main efforts were made with the aim to elucidate the major mechanisms of the energy transfer from Pr³⁺ to Ce³⁺ ions in the sodium polyphosphate systems.

2. Experimental details

Powder samples of NaPr_{1-x}Ce_xP₄O₁₂ (x=0; 0.01; 0.02; 0.04; 0.1; 0.25 and 0.5) were synthesized using the melt solution technique. XRD analyses were carried out with a STOE STADI P an automatic diffractometer. The details of this synthesis and the study of the microstructure of the typical crystal were described previously in [9].

Measurements of luminescence excitation and emission spectra as well as luminescence decay kinetics were performed at the Deutsches Elektronen Synchrotron (DESY, Hamburg) using the synchrotron radiation from the DORIS III storage ring and the facility of the SUPERLUMI experiment station at HASYLAB [10]. A helium flow cryostat has been used to stabilize the temperature in the temperature range of 10 -300 K.

Emission spectra were measured with a spectral resolution of about 1 nm using a 0.3 m ARC “Spectra Pro 308” monochromator-spectrograph in Czerny-Turner mounting equipped with a 300 grooves/mm gratings and a Princeton Instruments CCD detector. The emission spectra were not corrected for the spectral sensitivity of the detection system. Luminescence excitation spectra were scanned with a resolution of 0.3 nm within a 5-12 eV range by the primary 2 m monochromator in 15° McPherson mounting (equipped with Jobin Yvon holographic concave grating, Al+MgF₂ coating, 1200 grooves/mm) using HAMAMATSU R6358P photomultiplier at the secondary ARC monochromator. Luminescence excitation spectra have been corrected for the incident photon flux. A single photon counting technique was used for recording luminescence decay kinetics within a 200 ns time gate. This gate is defined by the excitation pulse frequency when the storage ring is operated in five bunch mode.

The X-ray excited emission spectra and decay kinetics studies were recorded using a laboratory X-ray source (anode voltage 40 kV, current intensity 0.2 mA) with pulse duration of 2 ns and repetition frequency of 100 kHz.

3. Sample characterizations

The XRD pattern of the polycrystalline sample with a nominal composition of NaPrP₄O₁₂ displays individual, narrow peaks, which characterized of well-crystallized single phase of NaPrP₄O₁₂ [11] are presented in figure 1. Composition of the phase and the set of analyzed diffraction lines lead to a structural model of the NaNdP₄O₁₂-type [12, 13] for Rietveld refinement. The crystal structure of the NaPrP₄O₁₂ compound with calculated unit cell lattice parameters $a=7.22526(6)$, $b=13.13416(15)$, $c=12.26449(18)$ Å and $\beta=125.6692(9)^\circ$ is actually isotypic with NaNd(PO₃)₄. The atomic arrangement in NaPrP₄O₁₂ practically corresponds to the same arrangement as in prototype NaNdP₄O₁₂ and other isostructural polyphosphates, e.g. NaGd(PO₃)₄ [14] and NaLa(PO₃)₄ [15]. The coordination polyhedron for praseodymium is distorted square antiprism [PrO₈] (CN = 8), which also can be described as dodecahedron formed by 12 triangle faces. The distorted octahedron [NaO₆] (CN = 6) and distorted tetrahedron [PO₄] (CN = 4) characterize the atomic environment for a sodium and a phosphorus, while a single atom (CN = 1) and a non-collinear two-atom environment (CN = 2) are typical for an oxygen. The [(PO₃)₄]⁴⁻ chains built from a corner-sharing [PO₄] tetrahedra and [PrO₈] dodecahedra form a 3D-framework; sodium ions situate in the intersecting tunnels of this framework. The distance between the nearest Pr³⁺ ions is about 5.759(2) Å. The same crystal structure and similar lattice parameters are obtained in the case of the Ce³⁺-doped NaPrP₄O₁₂ polyphosphates. For example, the distance between the nearest Pr³⁺ and Ce³⁺ ions in NaPr_{0.98}Ce_{0.02}P₄O₁₂ is 5.732(4) Å.

Figure 1. Observed and calculated X-ray powder profiles for the NaPrP₄O₁₂ compound. (Diffractometer STOE STADI P, Cu $K\alpha_1$ -radiation). Experimental data (crosses) and calculated profile (solid line through the crosses) are presented together with the calculated Bragg positions (vertical ticks) and difference curve (solid line below).

4. Results and discussion

4.1. Luminescence characteristics of $\text{NaPrP}_4\text{O}_{12}:\text{Ce}^{3+}$ observed under the synchrotron excitation

The excitation and emission spectra of the $\text{NaPr}_{1-x}\text{Ce}_x\text{P}_4\text{O}_{12}$ ($x=0, 0.1$) polyphosphates are displayed in figure 2. The low-temperature emission spectra of the undoped $\text{NaPrP}_4\text{O}_{12}$ measured upon the synchrotron excitation shows the intense $5d-4f$ luminescence of the Pr^{3+} ions in the 210-280 nm spectral range (figure 2(a)). However, the typical radiative transitions which correspond to the photon cascade emission in the Pr^{3+} ions are not detected like in the case of the undoped $\text{LiPrP}_4\text{O}_{12}$ polyphosphate [16]. This allowed us to assume, that the 1S_0 level of the Pr^{3+} ion locates higher than the lowest states of the $4f/5d$ configuration. In the excitation spectrum of $\text{NaPrP}_4\text{O}_{12}$ measured for the Pr^{3+} -related emission band ($\lambda_{\text{em}}=255$ nm) the broad absorption bands in the 230-150 nm spectral region correspond to transitions originating from the $\text{Pr}^{3+} {}^3H_4$ level to the $4f/5d$ states.

Figure 2. Excitation (solid lines) and emission (dashed lines) spectra measured (a) for undoped $\text{NaPrP}_4\text{O}_{12}$ and (b, c) for $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$.

The low-temperature emission spectrum of $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ polyphosphate measured upon the excitation in the $4f \rightarrow 5d$ cerium absorption ($\lambda_{\text{exc}}=168$ nm) shows the intense UV emission bands peaking at 310 and 328 nm, which correspond to the $5d_1 \rightarrow {}^2F_{5/2,7/2}$ radiative transitions of Ce^{3+} ions (figure 2(b)). The Ce^{3+} emission bands in $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ shifts to the longer wavelength range as compared with those for the $\text{LiPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ polyphosphate [17]. The excitation spectrum of $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ measured for the Ce^{3+} -related ($5d_1 \rightarrow {}^2F_{7/2}$) emission band ($\lambda_{\text{em}}=328$ nm) reveals the presence of a structure typical for the Ce^{3+} ion in a low-symmetry crystal field with a dodecahedral coordination around the Ce^{3+} ion. The intense broad bands with maximum at 4.20 eV (295 nm), 4.62 eV (268 nm), 4.92 eV (252 nm) and 5.39 eV (230 nm) corresponds to the transitions from the $4f$ ground state to the $5d$ excited states of the Ce^{3+} ion, respectively. The position of the $5d_5$ band is difficult to identify, since this band overlaps with the absorption edge of the undoped $\text{NaPrP}_4\text{O}_{12}$ polyphosphate. However, one may predict the

position of the $5d_5$ band in $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ using the crystallographic parameter $R_{\text{av}}=236.5$ pm (the average Pr–O bondlength in the $\text{NaPrP}_4\text{O}_{12}$ host lattice) and a dependence of the crystal-field splitting (ε_{cfs}) on the type and the size of an anion polyhedron around the cerium ions [18]. In the case of $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ the value of the crystal-field splitting is estimated to be $17\,300\text{cm}^{-1}$. Therefore, the position of the $5d_5$ absorption band may be at 6.35eV (195 nm). The crystal field splitting ε_{cfs} (the energy difference between the highest and lowest energy levels of the $5d$ band), the centroid shift ε_c (the average energy of the $5d$ bands), and the total redshift D for $\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$ are presented in table 1. The similar structure of the luminescence and excitation spectra for the sodium polyphosphate is observed at $T=300\text{ K}$. The decay curves of the Ce^{3+} $5d-4f$ luminescence upon the excitation in the Ce^{3+} $5d_1$ absorption band is exponential with the decay time $\tau=16.9\text{ ns}$ at $T=300\text{ K}$ (figure 4(d), curve 1).

Table 1. The spectroscopic and crystallographic parameters of sodium polyphosphates doped with Ce^{3+} ions; ddh is the abbreviation of dodecahedra.

Compound	Space group: polyhedra	Excitation bands, (nm)	Emission bands, (nm)	D (cm^{-1})	ε_{cfs} (cm^{-1})	ε_c (cm^{-1})	Ref.
$\text{NaGd}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$	$\text{P2}_1/\text{n}:(\text{ddh})$	196, 207, 218, 254, 297	313, 332	15 670	17 350	7 582	[19]
$\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$	$\text{P2}_1/\text{n}:(\text{ddh})$	195, 230, 252, 268, 295	310, 328	15 442	17 300	7 332	our

The cerium emission excites not only in the region of the cerium absorption, but also in the region of the praseodymium absorption, which leads to the efficient energy transfer process from Pr^{3+} to Ce^{3+} ions in $\text{NaPrP}_4\text{O}_{12}:\text{Ce}^{3+}$ polyphosphates. Additional confirmation of the nonradiative energy transfer from Pr^{3+} to Ce^{3+} is the decreasing of the decay time of the Pr^{3+} emission in $\text{NaPrP}_4\text{O}_{12}:\text{Ce}^{3+}$. Thus, the decay time of the Pr^{3+} luminescence measured upon the excitation with $\lambda_{\text{exc}}=174\text{ nm}$ changes from 10.3 to 1.05 ns with the Ce^{3+} concentration increasing (figure 3).

The decay curve of the Pr^{3+} emission in the case of $\text{NaPr}_{0.98}\text{Ce}_{0.02}\text{P}_4\text{O}_{12}$ (figure 3, curve 2) is approximated by the exponential curve with a high precision ($R^2=0.99\%$). The presence of the exponential stage in the decay curve corresponds to the emission of donors (Pr^{3+}), which transfer the electronic excitations to the ordered collective of acceptors (Ce^{3+}) located in the nearest positions to donors on the distance $R_{\text{min}}=5.732(4)\text{ \AA}$. The nonexponential stage in the decay curve of $\text{NaPr}_{0.98}\text{Ce}_{0.02}\text{P}_4\text{O}_{12}$, which reflects the energy transfer from donors to the disordered collective of acceptors replaced on the distance more than R_{min} , is absent. Hence, we can assume that in compounds with the high concentration of donors all acceptors locate on the nearest positions to donors. In this case the rate of the nonradiative transitions reaches the maximum (W_{max}) and is described as follows:

$$W_{\text{max}} = \frac{1}{\tau_0} - \frac{1}{\tau}, \quad (1)$$

τ_0 is the decay time of the Pr^{3+} emission in the undoped $\text{NaPrP}_4\text{O}_{12}$ and τ is the decay time of the Pr^{3+} emission in the Ce^{3+} -doped $\text{NaPrP}_4\text{O}_{12}$ polyphosphate. Simultaneously, W_{max} can be presented using the equation [20]:

$$W_{\text{max}} = 7C_{\text{DA}}nR_{\text{min}}^{-3} \quad (2)$$

Assuming the dipole character of the interaction between Pr^{3+} and Ce^{3+} ions and taking into account $R_{\text{min}}=5.732(4)\text{ \AA}$ together with the Ce^{3+} concentration $n=8.4\times 10^{19}\text{cm}^{-3}$ in $\text{NaPr}_{0.98}\text{Ce}_{0.02}\text{P}_4\text{O}_{12}$, the microparametr of donor-acceptor interaction (C_{DA}) is estimated as $4\times 10^{-2}\text{ nm}^6/\text{ms}$.

Figure 3. Decay curves of the Pr^{3+} luminescence for $\text{NaPr}_{1-x}\text{Ce}_x\text{P}_4\text{O}_{12}$ with different Ce^{3+} contents: $x=0$ (curve 1) $x=0.02$ (curve 2) and $x=0.1$ (curve 3) at $T=300$ K.

Figure 4. Decay curves of the Ce^{3+} luminescence ($\lambda_{\text{em}}=330$ nm) for $\text{NaPr}_{1-x}\text{Ce}_x\text{P}_4\text{O}_{12}$ (a) $x=0.002$, (b) $x=0.02$, (c) $x=0.1$ and (d) $x=0.1$ upon the different excitations at $T=300$ K

The presence of the rise-up stage in decay kinetic of the Ce^{3+} emission measured upon the excitation in the region of the Pr^{3+} absorption band ($\lambda_{\text{exc}}=160$ nm) also shows that the efficient energy transfer from Pr^{3+} to Ce^{3+} ions takes place (figure 4). The rise time for $\text{NaPr}_{0.998}\text{Ce}_{0.002}\text{P}_4\text{O}_{12}$ is $\tau_{\text{rise}}=4$ ns

and is much shorter as compared to the intrinsic decay time of the Pr^{3+} luminescence ($\tau=10.5$ ns). This fact indicates the absent of the radiative relaxation from the Pr^{3+} to Ce^{3+} ions in the $\text{NaPrP}_4\text{O}_{12}:\text{Ce}^{3+}$. From the other hand, the rise time reflects the time of the excitation energy migration via Pr^{3+} -sub-lattice. The rise time begins to decrease as the concentration of Ce^{3+} ions increases to $x=0.02$ ($\text{NaPr}_{0.98}\text{Ce}_{0.02}\text{P}_4\text{O}_{12}$ figure 4 (b)) and is almost absent in the case of $x=0.1$ ($\text{NaPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$, figure 4 (c)). As the concentration of Ce^{3+} ions increases, the rise time decreases rapidly in the decay curves of the Ce^{3+} luminescence measured upon the excitation in the Pr^{3+} absorption. This effect may indicate that another channel of the energy transfer can be realized in the Pr-base polyphosphates, when the concentration of Ce^{3+} ions is higher than $x=0.1$, namely, the direct nonradiative energy transfer from Pr^{3+} to Ce^{3+} without the energy migration via Pr^{3+} -sub-lattice. In the region of the band-to-band excitation, the decay curve of the Ce^{3+} luminescence consists of fast and slow components. The appearance of the slow component in the decay curve of the Ce^{3+} emission upon the excitation at $\lambda_{\text{exc}}=95$ nm is caused by the trapping process of the band electrons and holes till the moment of their recombination with Ce^{3+} centres (figure 4(d)).

4.2 Luminescence of $\text{NaPrP}_4\text{O}_{12}:\text{Ce}^{3+}$ upon X-ray excitation

The X-ray excited luminescence spectra of the $\text{NaPrP}_4\text{O}_{12}$ polyphosphates doped with different concentrations of Ce^{3+} ions are recorded at the integral mode and in the time window of 200 ns at $T=300$ K. The intensity of the Ce^{3+} luminescence in $\text{NaPrP}_4\text{O}_{12}$ upon the X-ray excitation depends strongly from the concentration of Ce^{3+} ions as shown in table 2. Analysis on the X-ray excited luminescence spectra of the $\text{NaPr}_{1-x}\text{Ce}_x\text{P}_4\text{O}_{12}$ series of polyphosphates shows broad emission bands with maximum at 314 and 330 nm, which attributes to the Ce^{3+} $5d-4f$ emission. The most intensive Ce^{3+} luminescence is obtained for $\text{NaPr}_{0.99}\text{Ce}_{0.01}\text{P}_4\text{O}_{12}$ and is presented in figure 5 (curve 1).

Table 2. Luminescence intensities of the $\text{NaPrP}_4\text{O}_{12}$ polyphosphates doped with the different concentration of Ce^{3+} ions upon the X-ray excitation.

Concentration (at%)	0	0.01	0.02	0.04	0.05	0.1	0.25	0.5
Intensity (arb.units)	54	74	66	43	41	39	24	4

Table 3. X-ray scintillation characteristics of the polyphosphate compounds.

Compounds	Light-yield (photons/MeV)	Decay time of fast component, ns	Contribution of fast component in luminescence spectrum, %	Ref
$\text{NaGd}_{0.99}\text{Ce}_{0.01}\text{P}_4\text{O}_{12}$	11 100	18.0	10	[3]
$\text{NaPr}_{0.99}\text{Ce}_{0.01}\text{P}_4\text{O}_{12}$	11 000	25.0	40	our
$\text{LiPr}_{0.9}\text{Ce}_{0.1}\text{P}_4\text{O}_{12}$	5 000	25.4	90	[16]

The decay kinetics for the $\text{NaPrP}_4\text{O}_{12}$ polyphosphates doped with different concentrations of Ce^{3+} ions under the X-ray excitation are also studied. The decay curves of the Ce^{3+} luminescence upon the X-ray excitation are an exponential, but consist of fast and slow components (figure 6 inset). The decay time of the fast component is estimated to be approximately 25 ns. However, this value larger than the intrinsic decay time of the Ce^{3+} luminescence, which was observed under the synchrotron excitation ($\tau=16.9$ ns). The reason of such difference is the deceleration of the excitation energy transfer from the ionization track to Ce^{3+} ions [21]. The appearance of the slow component in the decay curve of the Ce^{3+} luminescence can be the result of the recombination processes involving Pr^{3+} and Ce^{3+} ions. The intensities, decay times and relative contributions of the fast component (time window of 200 ns) in the luminescence spectrum upon the X-ray excitation in the Ce^{3+} -doped polyphosphate compounds one can compare in table 3.

In order to estimate the light yields of polyphosphates studied, the X-ray excited luminescence spectrum of BaF₂ was measured under the same experimental conditions (figure 5, curve 2). The light yield of BaF₂ is 8 880 photon/MeV [3]. Therefore, the light yield of the NaPr_{0.99}Ce_{0.01}P₄O₁₂ is estimated to be 11 000±1000 photon/MeV from the ratio of integral emission intensities of the sample and BaF₂. The relatively high light yield under the X-ray excitation and the presence of the fast component (40 %) in decay kinetic of NaPr_{0.99}Ce_{0.01}P₄O₁₂ indicates that the Pr-based polyphosphates doped with the Ce³⁺ ions can be suited for the detection of X-ray and gamma quanta.

Figure 5. X-ray excited emission spectra of NaPr_{0.99}Ce_{0.01}P₄O₁₂ (1) and BaF₂ (2) at $T=300$ K. In the inset, the decay curve of the X-ray excited Ce³⁺ emission at $T=300$ K.

5. Conclusions

The paper presents the structural characterization and the luminescence spectroscopy of the Pr³⁺-based polyphosphate materials doped with the Ce³⁺ ions upon the excitation with the synchrotron radiation and X-rays. The $5d_{1-4}$ excitation bands of Ce³⁺ ion are revealed at 4.20 eV (295 nm), 4.62 eV (268 nm), 4.92 eV (252 nm) and 5.39 eV (230 nm) and last $5d_5$ band 6.35 eV (195 nm) overlaps with the host-lattice absorption of NaPrP₄O₁₂. The processes of the excitation energy migration and the energy transfer from Pr³⁺ to Ce³⁺ were studied according to the analysis of excitation spectra, luminescent spectra and decay curves from the lower excited state levels of the $4f^15d^1$ and $5d^1$ electronic configurations of Pr³⁺ and Ce³⁺ ions, respectively. The influence of the doping concentration of Ce³⁺ ions on the luminescence characteristics of the NaPrP₄O₁₂:Ce³⁺ polyphosphates upon the X-ray excitation were investigated. The highest light yield of 11 000 ±1000 photon/MeV was estimated for the NaPr_{0.99}Ce_{0.01}P₄O₁₂ polyphosphate.

Acknowledgments

This work was partially supported by the 7 th FP INCO.2010-6.1 grant agreement No.266531 (project acronym SUCCESS) and by the Estonian Science Foundation grant No. 8678. The work of T. Shalapska was supported by the Marie Curie Actions Postdoctoral Research grant No. 0057J.

References

- [1] Zhong J, Liang H, Han B, Su Q, Tao Y 2008 *Chem. Phys. Letters.* **453** 192
- [2] Han B, Liang H, Ni H, Su Q, Yang G, Shi J, Zhang G. 2009 *Optics Express* **17** 7138
- [3] Zhong J, Liang H, Su Q, Zhou J, Khodyuk I V, Dorenbos P 2009 *Optical Materials* **32** 378
- [4] Stryganyuk G, Shalapska T, Pashyk I, Voloshinovskii A, Krasnikov A, Zazubovich S 2011 *J. Lumin.* **131** 2027
- [5] Chewpraditku W, He X, Chen D, Shen Y, Sheng Q, Yu B, Nikl M, Kucerkova R, Beitlerova A, Wanarak C, and Phunpueok A 2011 *Phys. Status Solidi a* **208** 2830

- [6] Nikl M, Yoshikawa A, Satonaga T, Kamada K, Sato H, Solovieva N, Beitlerova A and Fukuda T 2004 *Phys Status solidi a* **201** R108
- [7] Wang L, Zhang X, Hao Z, Luo Y, Zhang J and Wang X 2010 *J. Appl. Physics* **108** 093515
- [8] Wu Y, Ding D, Pan Sh, Yang F, Shi J, Ren G 2012 *J. Lumin.* **132** 251
- [9] Shalapska T, Stryganyuk G, Demchenko P, Voloshinovskii A and Dorenbos P 2009 *J. Phys: Condens. Matter* **21** 445901
- [10] Zimmerer G 2007 *Radiat. Meas.* **42** 859
- [11] Ferid M, Ben Hassen-Chehimi D, Kbir-Ariguib N and Trabelsi-Ayedi M 1994 *J. Therm. Analys.* **42** 913
- [12] Koizumi H 1976 *Acta Crystallogr. B* **32** 2254
- [13] Nakano J, Otsuka K, Yamada T 1976 *J. Appl. Phys.* **47** 2749
- [14] Amami J, Férid M, Trabelsi-Ayedi M 2005 *MRS Bullet.* **40** 2144
- [15] Zhu J, Cheng W-D, Wu D-S, Zhang H, Gong Y-J, Tong H-N 2006 *J. Solid State Chem.* **179** 597
- [16] Shalapska T, Stryganyuk G, Trots D, Romanuchun Yu, Gektin A, Voloshinovskii A and Dorenbos P 2010 *J. Phys. D: Appl. Phys.* **43** 405404
- [17] Shalapska T, Stryganyuk G, Trots D, Demkiv T, Gektin A, Voloshinovskii A and Dorenbos P 2010 *J. Lumin.* **130** 194
- [18] Dorenbos P 2001 *Phys. Rev. B* **64**, 125117
- [19] Zhong J, Liang H, Su Q, Dorenbos P, Dana Birowosuto M 2007 *Chem. Phys. Letter* **445** 32
- [20] Avanesov A G, Basiev T T, Voronko Yu K 1983 *JETP-Lett.* **84** 1028
- [21] Shalapska T, Stryganyuk G, Gektin A, Demchenko P, Voloshinovskii A and Dorenbos P 2010 *J. Phys.: Condens. Matter* **22** 485503