

IOPscience

Home Search Collections Journals About Contact us My IOPscience

YAG:Pr³⁺ transparent ceramics for applications in photonics: synthesis and characterization

This content has been downloaded from IOPscience. Please scroll down to see the full text. 2014 Mater. Res. Express 1 045903 (http://iopscience.iop.org/2053-1591/1/4/045903) View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 156.17.103.102 This content was downloaded on 15/02/2016 at 19:02

Please note that terms and conditions apply.

Materials Research **Express**

YAG:Pr³⁺ transparent ceramics for applications in photonics: synthesis and characterization

Enrico Cavalli^{1,2}, Laura Esposito², Marco Bettinelli³, Adolfo Speghini³, Konstantin V Ivanovskikh^{4,5}, Rosa B Hughes-Currie⁶ and Mathijs de Jong⁷

¹Dipartimento di Chimica, Università di Parma, Parma, Italy

³ Dipartimento di Biotecnologie, Università di Verona and INSTM, UdR Verona, Verona, Italy ⁴ ANK Service, Ltd, Novouralsk, Sverdlovsk reg., Russia

⁵ Institute of Physics and Technology, Ural Federal University, Ekaterinburg, Russia

⁶Department of Physics and Astronomy, University of Canterbury, New Zealand

⁷ Debye Institute for Nanomaterials Science, Utrecht University, Utrecht, The Netherlands E-mail: enrico.cavalli@unipr.it

Received 3 September 2014 Accepted for publication 29 September 2014 Published 20 October 2014

Materials Research Express 1 (2014) 045903 doi:10.1088/2053-1591/1/4/045903

Abstract

 $Y_3Al_5O_{12}$ (YAG) transparent ceramics doped with Pr^{3+} have been obtained by vacuum sintering of spray dried commercial powders and characterized by XRD and SEM techniques. A comprehensive spectroscopic investigation has then been carried out including: absorption spectra and decay time measurements in the visible-IR spectral region and x-ray and VUV excitation and emission properties studied with synchrotron radiation. The main processes responsible for the excited states dynamics have been identified and characterized. Comparison with the properties of the single crystal reveals that the investigated material has interesting perspectives for applications in optics and photonics.

Keywords: YAG:Pr³⁺, transparent ceramics, emission spectroscopy, VUV emission

1. Introduction

Yttrium aluminum garnet ($Y_3AI_5O_{12}$, YAG) crystals doped with Pr^{3+} demonstrating intense electron-dipole 5d–4f emission transitions have been extensively investigated in order to develop scintillators [1–3] and solid state lasers emitting in the UV and visible regions [4–6]. Several studies have been carried out, mainly concerning the structure of the electronic levels of Pr^{3+} in YAG [7–10], its emission dynamics [5, 11–13] and the Pr^{3+} site distribution [14, 15]. Pr^{3+} :YAG single crystalline films [16] and powders [17] have also been investigated. Moreover, Pr^{3+} has been used as optical probe to study the effect of the sintering conditions on the

² ISTEC-CNR, Faenza, Italy

structural properties of YAG nanoceramics [18]. The development of ceramic optical materials has been triggered by the idea for production of cost effective large size scintillators and laser media (see [19–23] and references therein). Good prospects for the garnet based ceramic scintillators, particularly LuAG:Pr and YAG:Ce, have been demonstrated in [22, 24, 25]. Considering the relevant scientific interest and the promising application of ceramic optical materials, it is challenging to extend the research on YAG:Pr and to explore the possibility for its fabrication in the form of transparent ceramics as well as to test its spectroscopic and dynamic properties. To produce a sample of YAG:Pr transparent ceramics we have used a sintering procedure successfully developed by one of us for Yb³⁺:YAG [26, 27]. A high quality of the sample obtained is supported with structural and morphological characterization that is accompanied with results of (time-resolved) spectroscopic investigation in the UV, visible and NIR regions. The measured properties have been compared with the literature data on Pr^{3+} : YAG single crystals in order to assess the effect of the morphology on the emission performance.

2. Experimental

2.1. Synthesis and structural characterization

The process applied for the synthesis of 1at% Pr^{3+} -doped YAG transparent ceramics has been discussed in detail in previous papers [28]. Y₂O₃ (Nanocerox, >99.99%), Al₂O₃ (Taimei TM-DAR, >99.99%) and Pr₆O₁₁ (Sigma Aldrich >99.9%) were used as starting materials. They were mixed in stoichiometric ratios and ball milled for 72 h after addition of 0.5 wt% of tetraethyl orthosilicate (TEOS) as sintering agent and 1 wt% polyethylene glycol 400 (PEG-400) as dispersant. The suspension was spray dried with a laboratory spray dryer (Mini Spray Dryer B-290, Büchi) and the spray dried powder was shaped in a pellet with a diameter of 1 cm and thickness of 2–3 mm by linear pressing in a metallic die at 100 bar followed by cold isostatic pressing (CIP) at 2500 bar. After heat treatment at 800 °C in order to remove residual organic impurities, the pellet was sintered at 1735 °C for 16 h under high vacuum (10⁻⁶ mbar) in a clean furnace. Finally, it was annealed at 1300 °C in air and then polished to optical grade.

The microstructure was investigated by scanning electron microscopy (SEM) (Quanta[™] 200 ESEM, FEI, The Netherlands) and the optical transmittance was measured using a Perkin Elmer UV/VIS Lambda 35 Spectrometer.

2.2. Spectroscopic measurements

X-ray excited measurements of emission spectra and emission decay kinetics were performed using synchrotron radiation at beamline 20BM (PNC/XSD) at the Advanced Photon Source (Argonne National Laboratory, US). Incident x-rays from a Si(111) double-crystal monochromator were toroidally focused to a spot size of about 500 to $400 \,\mu\text{m}^2$. The x-ray monochromator was detuned to 80% of the maximum signal and a Rh-coated planar mirror was also used for harmonic rejection. Fluorescent x–rays were monitored using a single-element Vortex Si-drift detector. The x-ray excited optical luminescence (XEOL) was studied in two ways. For the emission spectra, an Avantes AvaSpec-2048 CCD spectrometer, equipped with a 300 lines mm⁻¹ grating and 50 μ m slit yielding ~2 nm resolution, was used. For emission decay measurements, a Horiba microHR spectrometer with a 600 lines mm⁻¹ grating and Hamamatsu R928 room temperature photomultiplier tube was used. In both cases, optical emission was collected using collector lenses and transmitted to the spectrometers through optical fibres.

Time-resolved VUV spectroscopic measurements were performed using the SUPERLUMI experimental station at HASYLAB (DESY, Germany) upon excitation with the synchrotron radiation (SR) from the DORIS III storage ring. For the measurement of excitation spectra in the range 3.7-19 eV a 2 m monochromator in McPherson mounting with a resolution of 3.2 Å was used. The detection of the luminescence was performed with a 0.3 m ARC SpectraPro-308i monochromator equipped with a 600 lines mm⁻¹ grating and a high-speed R3809U-50S (Hamamatsu) microchannel plate detector. Time-resolved spectra were recorded in two independent time windows (TWs): 2-14 ns (fast) and 72-172 ns (slow). Time-integrated spectra were recorded counting the emission signal within the whole time period of 192 ns available between SR pulses at the normal (5) bunch mode (BM) of the storage ring. The measurements were performed in the ultra-high-vacuum chamber ($\sim 10^{-9} \text{ mbar}$). The excitation spectra were signal.

High resolution absorption spectra were measured with a spectroscopic setup equipped with a 300 W halogen lamp fitted with a 0.25 m Spex monochromator as source, and a 1.26 m Spex monochromator with a RCA C31034 photomultiplier or a PbS N.E.P cell to analyse and detect the output radiation. To record emission spectra in the visible region (440–830 nm) the setup was modified appropriately by altering the optical pathway and setting up a 450 W Xenon lamp instead of the halogen lamp. The NIR emission was excited using a 455 nm LED and recorded with a Zolix λ 300 monochromator in combination with an OCULUS detector. The emission decay curves in the visible range were recorded upon pulsed excitation using a tunable dye laser (D100, Quanta System) pumped by a Nd:YAG laser (SYL201, Quanta System), a 0.5 m monochromator (HR460, Jobin Yvon) equipped with a 1200 lines mm⁻¹ grating, a water cooled GaAs photomultiplier (Hamamatsu) and a 500 MHz digital oscilloscope (WaveRunner, LeCroy).

All the spectroscopic measurements have been carried out at room temperature.

3. Results

3.1. Microstructure and absorption spectrum

The 1% Pr^{3+} :YAG sample (figure 1(a)) exhibits after sintering a regular microstructure formed by equiaxed grains with a diameter ranging from 20 to 60 μ m and no evidence of large residual pores (figure 1(b)).

The XRD pattern (not shown), is identical to that obtained in previous cases [28] and indicates the formation of the title compound. The transmittance of the sample is close to the theoretical value of pure YAG ceramic samples [29], confirming that the presence of defects as pores or secondary phases, not highlighted with the conventional microstructural analysis, should be very limited and their size very small (figure 2).

The high resolution absorption spectrum has been measured in the 4000–24000 cm⁻¹ range and is shown in figure 3. The transitions from the ${}^{3}H_{4}$ ground state to the excited levels of Pr³⁺ have been assigned on the basis of previous literature data [7–10]. The most intense lines have FWHM (full width at half maximum) values of the order of 20–30 cm⁻¹, i.e. similar to those usually observed for single crystals, thus attesting the good quality of the obtained material.



Figure 1. (a) Pr:YAG transparent ceramic sample and (b) SEM microstructure of its fractured surface.



Figure 2. UV-visible transmittance spectrum of the Pr:YAG transparent ceramic sample.



Figure 3. 298 K absorption spectrum of 1% Pr³⁺:YAG transparent ceramic.



Figure 4. Emission spectrum of 1% Pr³⁺:YAG transparent ceramics upon excitation with x-ray synchrotron radiation. Inset shows decay curve of d–f emission (circles) and its fitting to the double exponential decay function (solid line).

3.2. Time-resolved luminescence spectroscopy upon excitation with synchrotron radiation

The x-ray excited emission spectrum of 1% Pr³⁺:YAG transparent ceramics is shown in figure 4. The structure of the spectrum and relative intensities of its features do not depend on the beam energy, ranging from 2.7 to 30 keV. The two broad emission bands extending from about 300 to 430 nm can be ascribed to the parity-allowed transitions from the lowest energy level of the 4f5d configuration of Pr³⁺ to the ³H_J and ³F_J levels of the 4f² configuration. The narrow lines bands in the 450–800 nm range are due to f–f transitions, and have been assigned according to the energy levels scheme deduced from the absorption spectrum. The decay profile cannot be satisfactorily fitted with a single exponential decay function, however, it is well reproduced with a function containing two exponential decay components with decay times of 6.2 and 20.3 ns and nearly equal amplitude (figure 4).

It is worth noting that the decay curve shows quite intense constant level (piling) which is due to overlay of slow (micro- or millisecond order) decay components excited by continuous sequences of excitation pulses arriving with a high repetition rate. This is typically observed in synchrotron radiation experiments (see [30] for details). An origin of slow decay components can be connected with the well-known problem of antisite defects (see [31, 32] and references therein) which may temporarily capture electrons from conduction band causing delayed recombination of electronic excitation (e–h pairs and excitons) on Pr^{3+} centers.

The time-resolved and time-integrated VUV emission and excitation spectra of 1% Pr³⁺: YAG transparent ceramics are shown in figures 5(a) and (b), respectively. The spectra on the graphs are normalized for the maximum intensity of time-integrated spectra to keep the aspect ratio of the time-integrated and the time-resolved spectra. The time-resolved spectra are scaled for a better visual perception. Apart from the fact of lower resolution, the time-integrated emission spectrum is fairly similar to that obtained upon x-ray excitation and can be assigned accordingly. The decay profile recorded for d–f emission band upon excitation at 163 nm, that correspond to the maximum of the excitation spectrum in the range of the host absorption (see below), is shown in the inset of figure 5(a). The decay profile is a single exponential with time



Figure 5. Time-integrated and time-resolved VUV emission (a) and excitation (b) spectra of 1% Pr³⁺:YAG transparent ceramics. The emission decay profile recorded monitoring d–f emission is shown in the inset.

constant of 15 ns, similar (or even longer, considering the doping level) to that observed in the case of the single crystal [1]. The build-up observed in the decay profile is characterised by a rise time of about 1.5 ns and is probably related to the excitation process, involving an energy transfer mechanism from host electronic excitations to Pr^{3+} ions.

The excitation spectra recorded in time-integrated mode and in fast TW closely follow each other within the range of 165–300 nm and slightly deviate at shorter wavelength when the intensity of signal detected in slow time window rises. The UV part of the spectra (210–300 nm) consists of two broad excitation features which are assigned to $Pr^{3+} 4f^2({}^{3}H_4) \rightarrow 4f5d$ transitions. Clearly, the features related to f-d transitions look unusually shaped if compared with those observed in excitation spectra of YAG:Pr single crystals [1-3] and the background level of the spectrum is quite high. We suppose that the reason for this can be connected with complicated ways for penetration and scattering of incident photons by pores in a ceramic sample [33] and saturation phenomena which are not rare in experiments with VUV synchrotron radiation when studying parity-allowed transitions of rare earth ions [34, 35]. Similar effects probably contribute to shaping of the excitation features observed below about 195 nm which are related to the fundamental optical absorption of the host. The onset of the host absorption corresponds to the formation of perturbed and self-trapped excitons [31, 36] which provide relatively fast energy transfer to Pr³⁺ ions as demonstrated by domination of fast TW signal. At shorter wavelength the spectra reveal decrease of intensity along with the development of slower emission dynamics. This is typically explained in terms of migration losses caused by the increase of the mean distance between electrons and holes created with the same photon [37, 38].

3.3. Visible and NIR emission

The visible emission spectrum of 1% Pr^{3+} :YAG (figure 6) consists of manifolds originating from the ${}^{3}P_{0}$ level, with the exception of two multiplets at 603 and at 690 nm assigned to transitions from the ${}^{1}D_{2}$ state.



Figure 6. Visible emission spectrum of 1% Pr³⁺:YAG transparent ceramic.



Figure 7. (a) ${}^{3}P_{0}$ emission decay profile recorded at 489 nm upon excitation at 465 nm (circles) and its fit to the Inokuti–Hirayama dependence (see text). (b) ${}^{1}D_{2}$ emission decay profile recorded at 612 nm upon excitation at 465 nm (circles) and its fit to double exponential function with account of the build-up stage (solid line) (see text).

Considering the fact that the resolution of the setup used for the optical excitation experiments is significantly higher than those adopted for the measurements upon x-ray and VUV excitation, the spectrum agrees well with the above-presented spectra. The Stark components of the multiplets are sharp (FWHM of the order of $20-30 \text{ cm}^{-1}$), as in the absorption spectrum. The intensity of the ${}^{3}P_{0} \rightarrow {}^{3}F_{2}$ hypersensitive transition at 650 nm is low, compatible with a small value of the Ω_{2} Judd-Ofelt parameter [39]. The decay profile of the ${}^{3}P_{0}$ emission (figure 7(a)) slightly deviates from the single exponential behaviour. The average decay time, τ_{av} , has been estimated using the formula [40]:

$$\tau_{av} = \frac{\int t \cdot I(t) \cdot dt}{\int I(t) \cdot dt} \tag{1}$$

where I(t) represents the luminescence intensity at time *t*. Its value is 8.1 μ s, whereas that of the radiative lifetime $\tau_{\rm R}$ calculated in the frame of the Judd–Ofelt Theory is 10.2 μ s [39]. The ³P₀ state can be depopulated non-radiatively through a ³P₀ \rightarrow ¹D₂ multiphonon relaxation (MPR) process and/or through cross relaxation processes of the type:

$$\begin{bmatrix} {}^{3}P_{0}, {}^{3}H_{4} \end{bmatrix} \rightarrow \begin{bmatrix} {}^{1}G_{4}, {}^{1}G_{4} \end{bmatrix} \text{ and } \begin{bmatrix} {}^{3}P_{0}, {}^{3}H_{4} \end{bmatrix} \rightarrow \begin{bmatrix} {}^{1}D_{2}, {}^{3}H_{6} \end{bmatrix}$$
(2)

that are not fully resonant (the former in particular) and therefore are assisted by phonons.

The energy gap between the ${}^{3}P_{0}$ and ${}^{1}D_{2}$ levels is around 3300–3400 cm⁻¹ [10] and the cutoff of the phonon spectrum in YAG is about 820 cm⁻¹ [41]. Thus, at least four high energy phonons are required to bridge the gap between the ${}^{3}P_{0}$ and ${}^{1}D_{2}$ levels. The efficiency of the MPR process should then be lower than that of the cross relaxation. We have tested the effectiveness of this mechanism by analyzing the decay curve of figure 7(a) using the Inokuti–Hirayama model for energy transfer in absence of migration [42]:

$$\phi(t) = A \cdot \exp\left[-\frac{t}{\tau} - \alpha \left(\frac{t}{\tau}\right)^{3/s}\right]$$
(3)

where $\phi(t)$ is the emission intensity after pulsed excitation, *A* is the intensity of the emission at t=0, τ is the lifetime of the isolated donor and s=6 for dipole–dipole (D–D), 8 for dipolequadrupole (D–Q) and 10 for quadrupole–quadrupole (Q–Q) interaction. The parameter α provides information on the probability of the energy transfer process:

$$\alpha = \frac{4}{3}\pi\Gamma\left(1 - \frac{3}{s}\right)N_{\rm a}R_0^3\tag{4}$$

where Γ is the gamma function, N_a the concentration of the acceptor expressed in ions per volume and R_0 is the critical distance. We have fitted the decay curve to equation (3) by considering a D–D process and taking A, τ and α as adjustable parameters. The obtained τ value is 9.6 μ s, practically coincident with the radiative lifetime (10.2 μ s [39]). The critical distance for the transfer, evaluated by means of equation (4), is about 10 Å, which is shorter than the statistically estimated mean shortest distance between the doping ions in the lattice (17 Å). The $\frac{\tau_{av}}{\tau_R}$ ratio, which provides an estimation of the quantum efficiency of the involved ${}^{3}P_{0}$ emission, results to be 0.79, a relatively high value. On the basis of these results we conclude that the efficiency of the cross relaxation processes (2) is not very high and probably related to the existence of Pr^{3+} pairs or clusters. The decay curve of the ¹D₂ emission, reported in figure 7(b) deviates from a single exponential behaviour. The average decay time, τ_{av} , evaluated using formula (1) is 91 μ s, significantly shorter than the radiative decay time, 198 μ s, estimated by Malinowski *et al* [39]. The quantum efficiency is in this case 0.46, i.e. lower than that of the ${}^{3}P_{0}$ level. It can be observed that the temporal profile of figure 7(b) presents a rise time, indicating feeding from an upper state. It has been reproduced by means of a double exponential plus rise time function, yielding decay times of 40 and 115 μ s and a rise time of 5 μ s, compatible with the decay time of the ${}^{3}P_{0}$ level. For the rest, we infer that the longer decay time can be ascribed to Pr^{3+} in regular sites, whereas the shorter one pertains to ions located at defect sites, namely in



Figure 8. NIR emission spectrum of 1% Pr³⁺:YAG transparent ceramic.

correspondence of grain boundaries, dislocations etc, or in the neighbourhood of other active ions (pairs, clusters) [43]. The fact that the 'regular' decay time is shorter than the radiative lifetime indicates that the ${}^{1}D_{2}$ state is in part depopulated through a cross relaxation process. The most probable mechanism is:

$$\begin{bmatrix} {}^{1}\mathrm{D}_{2}, {}^{3}\mathrm{H}_{4} \end{bmatrix} \rightarrow \begin{bmatrix} {}^{1}\mathrm{G}_{4}, {}^{3}\mathrm{F}_{4} \end{bmatrix}$$
(5)

which is nearly resonant, being strongly dependent on concentration and hardly influenced by temperature. Finally, the room temperature emission in the NIR region is reported in figure 8.

All the observed features have been assigned to transitions from the ${}^{1}D_{2}$ level, with the exception of the manifold in the 1300–1500 nm range that is ascribed to the ${}^{1}G_{4} \rightarrow {}^{3}H_{5}$ transition [44] and in part overlaps the ${}^{1}D_{2} \rightarrow {}^{1}G_{4}$ multiplet. The ${}^{1}G_{4}$ level is populated through cross relaxation from both ${}^{3}P_{0}$ and ${}^{1}D_{2}$ state (process (2) and (5), respectively).

The emission channels and the cross relaxation pathways of the investigated material are summarised in the scheme presented in figure 9.

4. Conclusions.

Fully dense transparent 1at % Pr^{3+} :YAG ceramic has been successfully produced by solid state sintering under high vacuum of spray dried commercial powders shaped by linear and cold isostatic pressing. The microstructure was examined with the SEM and was found to be homogeneous and fully crystalline with clean grain boundaries and residual porosity below the detection limit. The luminescence spectroscopic and dynamic properties have been investigated in the VUV, UV, visible and NIR spectral regions. All the observed transitions have been assigned and the decay kinetics of the main emission states have been characterized. To the best of our knowledge, this is the first report on the spectroscopic properties of Pr^{3+} :YAG in form of transparent ceramic. The comparison with the luminescence characteristics of Pr^{3+} :YAG single



Figure 9. Energy levels scheme and relaxation processes of Pr^{3+} :YAG transparent ceramic.

crystals, reported in literature, has evidenced the good quality of the ceramic sample and its attractive application perspectives, for example in the field of scintillator materials.

Acknowledgements

The authors wish to thank Dr R Gordon for help during the measurements the Advanced Photon Source.

This work has been partially supported by the Flag Project RITMARE, La Ricerca Italiana per il Mare, coordinated by CNR and funded by the Ministry of Education, University and Research within the National Research Program 2011–2013.

References

- Wisniewska M, Wisniewski D, Wojtowicz A J, Tavernier S, Lukasiewicz T, Frukacz Z, Galazka Z and Malinowski M 2002 *IEEE Trans. Nucl. Sci.* 49 926
- [2] Babin V, Krasnikov A, Maksimov Y, Nejezchleb K, Nikl M, Savikhina T and Zazubovich S 2007 Opt. Mater. 30 30
- [3] Drozdowski W, Lukasiewicz T, Wojtowicz A J, Wisniewski D and Kisielewski J 2005 J. Crys. Growth 275 709
- [4] Malinowski M, Joubert M F, Mahiou R and Jacquier B 1994 J. Phys. IV C4 541
- [5] Malinowski M, Joubert M F and Jacquier B 1994 Phys. Rev. 50 12367
- [6] Ganem J, Dennis W M and Yen W M 1992 J. Lumin. 54 79
- [7] Hooge F N 1966 J. Chem. Phys. 45 4504
- [8] Antic-Fidancev E, Lemaître-Blaise M, Caro P and Krupa J C 1987 Inorg. Chim. Acta 139 281

- [9] Moune O K, Rabinovitch Y, Tétard D, Pham-Thi M, Lallier E and Faucher M D 2002 Eur. Phys. J. D 19 275
- [10] Gruber J B, Hills M E, MacFarlane R G, Morrison C A and Turner G A 1989 Chem. Phys. 134 241
- [11] Malta L, Antic-Fidancev E, Lemaître-Blaise M, Dexpert-Ghys J and Piriou B 1986 Chem. Phys. Lett. 129 557
- [12] Turos-Matysiak R, Zheng H R, Wang J W, Yen W M, Meltzer R S, Łukasiewicz T, Świrkowicz M and Grinberg M 2007 J. Lumin. 122–123 322
- [13] Meltzer R S, Zheng H, Wang J W, Yen W M and Grinberg M 2005 Phys. Status Solidi (C) 2 284
- [14] Malinowski M, Szczepański P, Woliński W, Wolski R and Frukacz Z 1993 J. Phys. Condens. Matter 5 6469
- [15] Özen G, Forte O, Di Bartolo B and Collins J M 2007 J. Appl. Phys. 102 023110
- [16] Gorbenko V, Krasnikov A, Nikl M, Zazubovich S and Zorenko Y 2009 Opt. Mater. 31 1805
- [17] Zhou S, Fu Z, Zhang J and Zhang S 2006 J. Lumin. 118 179
- [18] Hreniak D, Bettinelli M, Speghini A, Łukowiak A, Głuchowski P and Wiglusz R 2009 J. Nanosci. Nanotech. 9 6315
- [19] Ikesue A, Aung Y L, Taira T, Kamimura T, Yoshida K and Messing G L 2006 Ann. Rev. Mater. Sci. 36 397–429
- [20] Nikl M, Laguta V V and Vedda A 2008 Phys. Status Solidi (B) 245 1701-22
- [21] Shirinyan G, Ovanesyan K L, Eganyan A, Petrosyan A G, Pedrini C, Dujardin C, Kamenskikh I and Guerassimova N 2005 Nucl. Instr. & Meth. in Phys. Res. A 537 134–8
- [22] Zych E and Brecher C 2000 J. Alloys Compd. 300-301 495-9
- [23] Ikesue A and Aung Y 2006 J. Am. Ceram. Soc. 89 1936-44
- [24] Shi Y, Nikl M, Feng X, Mare J A, Shen Y, Beitlerov A, Kucerkov R, Pan Y and Liu Q 2011 J. Appl. Phys. 109 013522
- [25] Nikl M, Mare J A, Solovieva N, Li H, Liu X, Huang L, Fontana I, Fasoli M, Vedda A and D'Ambrosio C 2007 J. Appl. Phys. 101 033515
- [26] Serantoni M, Piancastelli A, Costa A L and Esposito L 2012 Opt. Mater. 34 995
- [27] Alderighi D, Pirri A, Toci G, Vannini M, Esposito L, Costa A L, Piancastelli A and Serantoni M 2010 Opt. Mater. 33 205
- [28] Cavalli E, Esposito L, Hostaša J and Pedroni M 2013 J. Eur. Ceram. Soc. 33 1425
- [29] Springer R M and Thomas M E 2013 IEEE J. Quantum Electr. 49 667
- [30] Wisniewski D and Boatner L A 2009 IEEE Trans. Nucl. Sci. 56 3806
- [31] Zorenko Y, Gorbenko V, Konstankevych I, Voloshinovskii A, Stryganyuk G, Mikhailin V, Kolobanov V and Spassky D 2005 J. Lumin. 114 85
- [32] Ueda J, Tanabe S and Nakanishi T 2011 J. Appl. Phys. 110 053102
- [33] Boulesteix R, Maître A, Baumard J-F, Rabinovitch Y and Reynaud F 2010 Opt. Express 18 14992
- [34] Stryganyuk G and Zimmerer G 2008 Phys. Solid State 50 1631-8
- [35] Stryganyuk G et al 2008 J. Lumin. 128 1937–41
- [36] Babin V, Bichevin V, Gorbenko V, Kink M, Makhov A, Maksimov Y, Nikl M, Stryganyuk G, Zazubovich S and Zorenko Y 2011 Phys. Status Solidi (B) 248 1505–12
- [37] Kamenskikh I A, Mikhailin V V, Shpinkov I N and Vasil'yev A N 1989 Nucl. Instr. Meth. Phys. Res. A 282 599
- [38] Mikhailin V V, Belsky A N, Kamenskikh I A, Kolobanov V N, Orekhanov P A, Shpinkov I N, Spassky D A and Vasil'ev A N 2002 Nucl. Instrum. Methods Phys. Res. A 486 367
- [39] Malinowski M, Wolski R and Woliński W 1990 Solid State Comm. 74 17
- [40] Shionoya S and Yen W M 1999 Phosphor Handbook (Boca Raton, FL: CRC Press)
- [41] Lukowiak A, Wiglusz R J, Maczka M, Gluchowski P and Strek W 2010 Chem. Phys. Lett. 494 279
- [42] Inokuti M and Hirayama F 1965 J. Chem. Phys. 43 1978
- [43] Ozen G, Collins J, Bettinelli M and Di Bartolo B 2013 Opt. Mater. 35 1360
- [44] Garapon C, Malinowski M, Joubert M F, Kaminskii A A and Jacquier B 1994 J. Phys. IV C4 349