Can Pr-Doped YAP Scintillator Perform Better?

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Abstract—A numerous set of Pr-doped YAP single crystals was prepared using Czochralski and micro-pulling down methods. Crystals codoped by bi-, tri- and tetravalent ions were prepared by the latter method as well. The scintillation performance of all the prepared materials was evaluated using radioluminescence, photoelectron yield and scintillation decay measurements at room temperature. The influence of shallow traps was studied by means of thermoluminescence in the 10–350 K temperature range. Though the intrinsic scintillation efficiency of Pr-doped YAP is higher than that of YAP:Ce, enhanced delayed radiative recombination processes are found to be responsible for lower-than-expected photoelectron yield of the former system. The possibilities of further optimization of Pr-doped YAP scintillator are discussed.

Index Terms—Luminescence, photoelectron yield, Pr-doped YAP, scintillator, thermoluminescence.

I. INTRODUCTION

THE luminescence characteristics of Ce^{3+} -doped YAlO_3 (YAP) single crystal, namely an intense emission band at about 360 nm and a decay time of the $5d_1 - 4f$ transition of Ce^{3+} of about 18 ns, were reported in the early 1970s by M. Weber [1]. The favorable properties of this material as fast scintillator were revealed some years later [2]. A considerable effort to increase its low density and low effective atomic number (Z_{eff}) by partial or complete substitution of Lu for Y ion was made in the 1990s (see [3] for a review). However, the growth of such crystals was

troubled by the narrow region of stability of the perovskite phase due to the smaller radius of the Lu cation.

Pr^{3+} doping was studied in a number of fluoride and oxide compounds in the search for photon cascade emission [4], while it was considerably less investigated for scintillation purposes [5]. Only recently, more systematic comparative studies were performed in the group of aluminum garnets and orthosilicates [6] where LuAG:Pr appeared as a new promising scintillator [7]. Pr doping was also pursued in the YAP host resulting in the high energy shifted $5d_1 - 4f$ emission peaking at about 245–250 nm with the scintillation decay time of about 13 ns [8]. Other works confirmed such a fast scintillation response of the Pr-doped YAP and LuAP single crystals, however, with respect to the Ce-doped analogues these materials provide much lower light yield [9]–[12]. Based on the fact that both Ce^{3+} and Pr^{3+} centers in YAP should act as the hole traps and that the scintillation mechanism is supposed to be analogous in both cases the reason for such a discrepancy in the light yield is difficult to understand. Therefore further optimization of Pr-doped aluminum perovskite remains an open problem.

In this contribution we compare scintillation efficiency (radioluminescence intensity), photoelectron yield and scintillation decay in an extended set of YAP:Pr crystals prepared by three different technological methods. The effect of various codoping ions is studied as well. Furthermore, the differences in Ce-doped and Pr-doped YAP single crystals in the energy migration and trapping mechanisms are evidenced using the thermoluminescence measurements. Electron spin resonance provides an additional insight into the nature of the involved defects and traps. Based on the achieved understanding, we discuss possibilities of further optimization of Pr-doped aluminum perovskite scintillators.

II. SAMPLES AND EXPERIMENTAL TECHNIQUES

The YAP samples used in this study are i) standard Ce-doped crystal (0.5 at%) grown by Czochralski technique (Cz) with 4N purity starting materials from molybdenum (Mo) crucible in CRYTUR Ltd (Czech Republic) which is used as a reference sample; the crystal with lower doping level (0.05%) grown by Czochralski technique with 4N purity starting materials from iridium (Ir) crucible in IMRAM, Tohoku university (Japan); ii) altogether twenty three Pr-doped (0.005–5%) and (Mg, Si, Zr, Hf, Ga, Mo, 0.005–0.5%) codoped crystals grown in IMRAM, Tohoku University (Japan) by the micro-pulling down method (mPD) with 4N purity starting materials from iridium crucible, (iii) Pr-doped crystal (0.5 and 1.1%), Cz-grown with 4N purity starting materials from molybdenum crucible in CRYTUR Ltd. All concentrations are given in molar percent and refer to the melt. From now on the samples will be denoted by abbreviations indicating the dopant, concentration, growth method

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Fig. 1. Radioluminescence spectra of Ce and Pr-doped YAP at RT. Excitation by X-ray, 40 kV. Spectra are mutually comparable in an absolute scale.

and crucible type (for example, Pr-5%(mPD,Ir)). The samples for experiments were prepared from parent crystals by cutting the plates of dimensions $7 \times 3 \times 1 \text{ mm}^3$ (mPD) and $7 \times 7 \times 1 \text{ mm}^3$ (Cz) and polishing them to an optical grade. Codoping of YAP:Pr crystals was used as a tool to change an internal equilibrium of the point defects in YAP host. In case of aliovalent codopants we follow the strategy successfully used by some of us in the case of trivalent-ion-doped PbWO_4 [3], [13]). In case of trivalent codopants the goal was either to influence the concentration of antisite defects, the existence of which in YAP host was recently proved by NMR [14], or to use it for the band gap engineering. Recently we have successfully applied the latter concept in the Ga-admixed LuAG:Pr [15].

Radioluminescence spectra, excited by an X-ray tube (W cathode), were measured by a modified 199S Edinburgh Instrument spectrofluorometer equipped with single grating monochromators and a photon counting photomultiplier-based detector. Conditions of experiment, including geometry, were carefully kept the same to enable comparison of the spectra within the sample set in an absolute scale (Figs. 1 and 6 in Section III). Photoluminescence and scintillation decays were measured by the same set-up using the time-correlated single photon counting method. H_2 -filled nanosecond flashlamp and ^{22}Na radioisotope were used for the excitation, respectively. In the latter case we used the concept of Bollinger and Thomas [16] with the fast plastic scintillator in front of the “Start” photomultiplier. Absorption spectra were measured by a UV-VIS-NIR Shimadzu UV-3101PC spectrophotometer. All these measurements were performed at room temperature (RT).

At RT the N_{phels} photoelectron yield, energy resolution (calculated from FWHM of the photopeak) and proportionality of N_{phels} were measured by new set-up with a hybrid photomultiplier (HPMT), model PPO 475B, manufactured by DEP company, Roden, the Netherlands, and multichannel analyzer in the pulse-height-analysis mode [17], [18]. For smaller samples (mPD-grown) the N_{phels} measurements were carried out under the excitation of ^{109}Cd (22.2 and 88 keV) and ^{241}Am (~ 16 and 59.6 keV) because in this range the YAP host has much higher linear attenuation coefficient than in the range above 200 keV. For larger YAP:Ce and YAP:Pr Cz-grown samples

with higher N_{phels} yield the measurements were carried out in the wider energy range up to 1275 keV using also ^{57}Co , ^{22}Na and ^{137}Cs energy lines. All the samples were measured at 1 μs shaping time and several selected Ce- and Pr-doped ones were additionally studied within a wider shaping time range of 0.5–10 μs to compare their N_{phels} time dependence.

TSL measurements after x-irradiation at 10 K and with a heating rate of 0.1 K/s were performed in the 10–310 K temperature range with a home-made apparatus featuring a CCD detector (Jobin-Yvon Spectrum One 3000) coupled to a monochromator (Jobin-Yvon Triax 180) with 300 and 100 grooves/mm gratings operating in the 278–713 nm and 138–1447 nm ranges. In this case x-ray irradiations were performed by a Philips 2274 tube operating at 20 kV.

III. RESULTS AND DISCUSSION

RT radioluminescence spectra of selected YAP samples doped exclusively with Pr are compared in absolute scale with those of Ce-0.5%(Cz,Ir) standard and Ce-0.05%(Cz,Ir) samples in Fig. 1.

The wide double band with maxima at about 242 nm and 280 nm is due to Pr^{3+} radiative transition from its $5d_1$ level. The former peak includes transitions to $^3\text{H}_4$ and $^3\text{H}_5$ levels, while the latter includes those to $^3\text{H}_6$ and $^3\text{F}_x$ ($x = 2, 3, 4$). A better spectral resolution of separate transitions in the spectrum is achieved at low temperature [11]. An integral of emission spectra in the region of fast $5d - 4f$ emission (200–450 nm) can be considered as the measure of the overall scintillation efficiency. The integral values are higher in all the Cz-grown Pr-doped YAP samples with respect to that of the Ce-0.5%(Cz,Mo) standard sample, see Table I. It is worth noting considerably lower radioluminescence intensity in the case of mPD grown sample: such effect has been already noticed in the case of systematically studied Yb-doped YAP [19], [20] and could be assigned to possibly inferior crystal quality with respect to Cz-grown crystals and radial dependence of the dopant segregation which is a frequent problem in mPD-grown crystals [21].

It is interesting to note the change of the intensity ratio of the $5d - 4f$ emission peaking at 242 nm and $4f - 4f$ emission lines around 490 nm (from $^3\text{P}_0$ level) and 620 nm (from $^1\text{D}_2$ level): the $4f - 4f$ emission intensity becomes relatively more intense with increasing Pr concentration. This effect has been already noticed [12], [22] and ascribed to a possible cross-relaxation effect between nearby lying Pr^{3+} ions [12]. Such a process can be enabled by the fact that $5d_1 - 4f$ emission is located at 242 nm, the half wavelength of that related to $(4f - 4f)^3\text{P}_0 - ^3\text{H}_4$ radiative transition at about 490 nm. Therefore, the former one photon transition can be directly converted into the latter two photon transition. Nevertheless, we do not observe any shortening of nanosecond decay times of $5d - 4f$ emission up to 1% of Pr doping level in YAP host (about 8 ns at RT [22]). In addition, only $\sim 25\%$ shorter decay time is obtained for Pr-5%(mPD,Ir) sample. Therefore, the possibility that cross-relaxation process involves the relaxed $5d_1$ level of Pr^{3+} is rather unlikely, because the intensity ratio of the above mentioned d-f and f-f emissions changes from 1: 0.07 in Pr-0.1%(mPD,Ir) to 1:0.5 in Pr-5%(mPD,Ir) sample and absolute intensity of $5d - 4f$

TABLE I
PHOTOELECTRON YIELD AND RELATIVE SCINTILLATION EFFICIENCY OF PR-DOPED YAP SAMPLES IN COMPARISON WITH YAP:Ce STANDARD SAMPLE. MEASUREMENTS OF THE FORMER WERE CARRIED OUT WITH SHAPING TIME OF $1 \mu\text{s}$ AND UNDER EXCITATION BY ^{137}Cs (662 keV) RADIOISOTOPE AND ^{241}Am (59.6 keV) FOR THE CZ-GROWN SAMPLES AND mPD GROWN SAMPLES, RESPECTIVELY. THE VALUES OF THE LATTER ARE DERIVED FROM THE INTEGRAL OF RADIOLUMINESCENCE SPECTRA, SEE FIGS. 1 AND 6.

Sample	Concentr. Melt (%)	Growth method & Crucible	$N_{\text{phels}}/\text{MeV}$ (phels per MeV)	FWHM (%) at 662 keV	N_{phels} % of standard	RL_intens. % of standard
YAP:Ce Japan	Ce-0.05	CZ - Ir	1978	7.3	71	81
YAP:Ce Czech	Ce-0.5	CZ - Mo standard	2803	4.8	100	100
YAP:Pr Japan	Pr - 0.05	CZ - Ir	2280	7.1	81	147
YAP:Pr Japan	Pr - 1.0	CZ - Ir	1026	8.9	37	113
YAP:Pr Czech	Pr - 0.5	CZ - Mo	975	10.3	35	130
YAP:Pr Czech	Pr - 1.1	CZ - Mo	1127	9.1	40	n.m.
mPD - grown samples				FWHM (%) at 59.6 keV		
YAP:Pr Japan	Pr-0.05	mPD - Ir	1015	46.3	36	91
YAP:Pr Japan	Pr - 0.1	mPD - Ir	1203	54.9	43	96
YAP:Pr Japan	Pr - 0.5 Hf 30ppm	mPD - Ir	619	40.7	22	56
YAP:Pr Japan	Pr - 0.5 Hf 60ppm	mPD - Ir	961	51.3	34	n.m.
YAP:Pr Japan	Pr - 0.5 Hf 120ppm	mPD - Ir	1262	~ 25	45	102
YAP:Pr Japan	Pr - 0.5 Hf 300ppm	mPD - Ir	1270	~ 30.	45	64
YAP:Pr Japan	Pr - 0.5 Mo-0.05	mPD - Ir	492	35.1	18	45

n.m. = not measured

Fig. 2. RT photoluminescence decay of the 490 nm emission line, $\lambda_{\text{exc}} = 450 \text{ nm}$.

Fig. 3. RT 4f - 4f photoluminescence spectra of Pr-doped YAP, $\lambda_{\text{exc}} = 450 \text{ nm}$.

emission decreases more than six times in the latter sample [22]. Moreover, a strong quenching of the 4f - 4f emission lines is evidenced by decay times shortening from $12 \mu\text{s}$ and $140 \mu\text{s}$ (Pr 0.1%) to $2 \mu\text{s}$ and $1 - 2 \mu\text{s}$ (Pr5%) in the 490 nm and 620 nm 4f - 4f emission lines, respectively, see Fig. 2 and [23].

The f-f emission of Pr^{3+} in YAP is of interest mainly for lasing [24] or upconversion-related [25] purposes. However, it can also be of interest in the present case, since possible pairing or clustering of Pr ions in YAP host could be monitored by the

change of mutual intensities of the f-f emission lines (e.g., in ranges from 490 to 510 nm and from 610 to 630 nm). Mutual emission line intensities apparently depend on Pr concentration and may reflect changes in the symmetry of Pr site and its nearest neighbourhood, see Figs. 1 and 3.

Scintillation decay of the YAP:Pr samples (the set presented in Fig. 1) shows a typical two-exponential character, see Fig. 4. Since the slower component with the decay time of about several hundred ns can hardly be distinguished, its decay time and

Fig. 4. RT scintillation decay of Pr-1%(Cz,Ir) sample, spectrally unresolved, excited by 511 keV photons of ^{22}Na radioisotope. Solid line is the convolution of instrumental response and function $I(t)$ in the figure. Faster and slower component percentage fractions of total intensity are shown next to the $I(t)$ formula. A construction of the coefficient α is sketched, see also [26]. True background level is given by the electronic noise of the photodetector.

calculated relative intensity of 38% are only indicative. Nevertheless, even much slower decay components do exist. Their decay time is comparable with the inverse repetition rate of the excitation pulse (10–20 kHz) as reflected by the increased level of the “background” before the signal rising edge (cf. Fig. 4). The fraction of intensity contained in slow components is expressed by the α coefficient, see [26] for details.

The dominant component has a decay time 8–9 ns, and releases about 40% of light intensity (calculated from the fit of the decay curve), the values consistent with the previous data [8]–[12]. Such fast decay promotes YAP:Pr to the category of the fastest scintillators based on $5d - 4f$ radiative transition in the UV-visible spectral range.

Preparation of a numerous set of the codoped samples of YAP:Pr was enabled by the flexible and fast mPD growth technique [27]. Some scintillation characteristics of the Zr and Si codoped YAP:Pr have been already published in our previous work [9], [28]. As mentioned in Section II the aim of codoping is to change the internal equilibrium of the YAP host defects due mainly to cation nonstoichiometry, presence of antisite defects and lack of oxygen anions. Their presence is determined by the technology, namely by the melt stoichiometry, growth atmosphere and post-growth treatments. The Mg^{2+} , Si^{4+} , Zr^{4+} , Hf^{4+} , $\text{Mo}^{3+(4+)}$ and Ga^{3+} codopants were tested and their influence on the optical, luminescence and scintillation characteristics of YAP:Pr was studied.

In the absorption spectra of codoped crystals the parasitic (defect-related) absorption bands are frequently observed. Some examples are given in Fig. 5. In the as-grown Pr-0.1% Mg-0.01% (mPD,Ir) sample and in several other samples annealed in air at 1200°C for several hours a broad absorption band extending up to 600 nm was observed. It was reported that absorption bands around 2.1–2.3 eV and 3.1–3.3 eV can be related to the O^- -based hole centers in YAP structure [29], [30]. At the same time the latter band can be also related to charge transfer transition from the valence band (oxygen ligands) towards Pr^{4+} center [31], [32]. F^+ center (one electron in oxygen vacancy) has been recently proved in YAP structure by EPR experiment [14] and can contribute to the observed absorption

Fig. 5. Absorption spectra of selected codoped YAP:Pr crystals prepared by mPD growth technique. The position and tentative origin of the absorption bands are indicated.

around 4.3 eV [33]. The smooth structureless absorption within 235–260 nm, adjacent to the edge of $^3\text{H}_4 - 5d_1$ absorption transition of Pr^{3+} at 5.3 eV (234 nm), is most probably related to the same absorption transition of slightly perturbed Pr^{3+} ions which is very well known issue e.g., in CeF_3 single crystals [3]. Only in the Mo-codoped samples an absorption band around 4.6 eV appears. Its amplitude correlates with the Mo concentration in the melt. It can be assigned to the charge transfer transition between the valence band and Mo^{4+} and/or between Mo^{3+} and the conduction band [34]. Apparently, most of these absorption bands overlap with the $5d_1 - 4f$ emission of Pr^{3+} so that their presence in bulk crystals must be minimized. A specific problem of the YAP structure consists in negative effect of cationic nonstoichiometry as it always results in the presence of triply charged cation vacancies which can stabilize various O^- -based centers nearby. Such centers are indeed observed with the help of EPR measurements [14], [22].

Radioluminescence spectra of practically all the codoped samples show clear enhancement of the $4f - 4f$ emission lines (relative to $5d_1 - 4f$ emission) with respect to samples without codoping. The reduction of absolute intensity of the $5d_1 - 4f$ band occurs as well, see Fig. 6 and Table I. Comparing crystals with different codopants, the most promising result was obtained for the Hf-codoped samples with Hf concentration around 120–160 ppm. Their spectral shape and RL intensity are comparable or slightly superior to those of the Pr-only doped YAP grown by the mPD method, see Fig. 6. It is interesting to note that similar concentration of trivalent dopants in PbWO_4 was found to provide maximum optimization of scintillation performance mainly due to the suppression of oxygen vacancies and unknown deep hole traps, see [3], [13] for the review.

The scintillation decay of codoped samples shows the similar shape and decay time values as those displayed in Fig. 4. In the case of Zr and Hf codoping the fast component becomes somewhat more intense (containing about 60–70% of total intensity calculated from the decay curve fit).

Photoelectron yield, energy resolution and proportionality of the N_{phels} yield were measured for an extended set of samples, see Table I and [9]. In the upper and bottom part of Table I

Fig. 6. Radioluminescence of the Hf-codoped YAP:Pr compared to the Ce-0.5%(Cz,Mo) standard sample. Excitation by X-ray tube, 40 kV, RT. Spectra are mutually comparable in an absolute scale.

Fig. 7. N_{phels} per 1 MeV photoelectron yield time development of the selected Ce- and Pr-doped YAP. Error of the measured values is $\pm 5\%$.

the Cz-grown and mPD-grown samples are grouped, respectively. In the case of N_{phels} and scintillation efficiency values the mPD-grown samples are clearly performing worse. Dependence of N_{phels} yield on the shaping time for selected Ce- or Pr-doped Cz grown crystals is presented in Fig. 7. As evident, there is no observable difference among these crystals. Rather flat observed time dependence of N_{phels} is consistent with the shape of scintillation decay in Fig. 4 where only barely visible slower decay component is present. In case of the energy resolution in Cz grown crystal set the best Ce-0.5% standard sample (4.8% at 662 keV) is outperforming the best Pr-0.05% doped crystal (7.1% at 662 keV) which might be influenced by somewhat lower N_{phels} value of the latter.

The proportionality of the N_{phels} yield is shown in Fig. 8 for selected Ce- and Pr-doped YAP samples. In this case the proportionality of the Ce-0.5% standard sample is worse than the best Pr-0.05% doped crystal. The proportionality of other Cz grown YAP:Ce from Mo crucible is presented in [17] and its proportionality is found between 90 and $\sim 102\%$ in the same range of energies.

The last two columns of Table I report the relative comparison of scintillation efficiency and photoelectron yield of all the samples with those of the Ce-0.5%(Cz,Mo) standard sample. One can notice an apparent inconsistency in the high scintillation efficiency (proportional to the integrated $5d-4f$ radioluminescence spectra measured in an absolute scale as in Figs. 1 and 6)

Fig. 8. The non-proportionality of the $N_{\text{phels}}(E)$ photoelectron yield of Ce-doped crystals (dimensions $\varnothing 10 \times 10 \text{ mm}^3$). Data normalized at 662 keV. Error of the measured values is $\pm 5\%$.

and much lower photoelectron yield for all the Pr-doped YAPs. This can be explained assuming that in the Pr-doped samples there is an enhanced delayed radiative recombination at Pr^{3+} centers due to unidentified trapping processes in the transport stage of the scintillation mechanism. Such processes must occur in the time scale of several tens of microseconds or longer as suggested by the above mentioned increased background signal in the scintillation decay measurement monitored by the alpha coefficient [26].

The presence of shallow trapping states in a scintillator can be monitored by TSL measurements below RT. Moreover, the correlation between TSL and EPR measurements can shed light on the nature of the involved trapping states, but only if they are paramagnetic. Unfortunately EPR cannot be used to monitor the presence of Pr^{3+} since it is not paramagnetic; moreover, to our knowledge there are also no EPR data in the literature for Pr^{4+} which has the same electronic configuration as the Ce^{3+} paramagnetic center. Low temperature wavelength-resolved TSL measurements were performed on some of the here reported samples [35]. In Fig. 9 we show typical glow curves of undoped, Ce-doped and Pr-doped YAP. In undoped YAP the glow peaks within 150–250 K were assigned to defect-stabilized O⁻ centers [14], [34], [35]. The proposed recombination process involves the thermal release of holes from specific trap and their radiative recombination with electrons stored in oxygen vacancies (giving rise to TSL glow peaks) and/or their localization in deeper traps. In the case of Ce or Pr-doped samples the glow curve changes noticeably. It is the consequence of the supposed hole trap character of both Ce^{3+} and Pr^{3+} ions which compete with intrinsic O⁻-based traps in the hole capture. However, unlike in aluminum garnets where TSL glow curves of Ce and Pr-doped samples are similar [36], they manifest considerable differences in YAP host. As discussed in detail in Ref. 35, a kind of complex defect is created around Ce^{3+} and Pr^{3+} dopant ion, in which electron and hole traps are spatially correlated as also evidenced by an additional athermal tunneling recombination process (flat structureless TSL signal occurring at temperatures lower than the principal TSL peak). TSL spectra display only the well-known bands of Ce^{3+} or Pr^{3+} [35] demonstrating that the final radiative recombination occurs at the doped rare earth ion. However, the composition and/or

Fig. 9. TSL glow curves after x-irradiation at 10 K of undoped, Ce-doped and Pr-doped YAP. See also [29].

configuration of such a complex defect does not seem to be the same for both Ce^{3+} and Pr^{3+} dopants. Nevertheless, an important conclusion can be drawn from Fig. 9: as the dominant glow curve peak occurs at a much higher temperature in the case of Pr doping, the lifetime of the filled trap at RT is about one order of magnitude longer with respect to that in Ce-doped YAP (compare the values reported in Fig. 9). This can be one of the reasons why the mentioned delayed radiative recombination processes in YAP:Pr are more pronounced and the photoelectron yield is lower with respect to that of YAP:Ce, despite the higher scintillation efficiency evaluated from YAP:Pr radioluminescence spectra.

IV. CONCLUSION

The scintillation performance of a numerous set of Pr-doped YAP single crystals prepared by three different technologies was evaluated by radioluminescence, photoelectron yield and scintillation decay measurements. The intrinsic scintillation efficiency of the best Czochralski grown YAP:Pr reached about 150% of that of YAP:Ce standard sample. However, its photoelectron yield is only about 80% of that of YAP:Ce standard suggesting the presence of enhanced delayed radiative recombination processes in YAP:Pr. The discrepancy between scintillation efficiency and photoelectron yield is systematically observed in all the Pr-doped samples. The mPD grown samples show on average an inferior quality with respect to the Czochralski grown ones. Thermoluminescence measurements in the 10–350 K temperature range manifest that in YAP:Pr the dominant glow curve peak occurs at a noticeably higher temperature (192 K) with respect to that found in YAP:Ce (115 K). The calculated RT lifetime of the 192 K peak-related trap in YAP:Pr is about one order of magnitude longer (1 ms) than that related to the 115 K peak in YAP:Ce. It can be one of the reasons of the decrease of photoelectron yield in YAP:Pr due to an enhanced delay in the transport stage of scintillation mechanism. However, since the existence of the mentioned delayed radiative recombination processes in YAP:Pr is due to a defect instead of being an intrinsic

property of this material, the possibilities to further optimize the scintillation performance of YAP:Pr remain open. As its intrinsic scintillation efficiency even exceeds that of YAP:Ce, also its photoelectron yield could become superior if the degrading defects and related traps are suppressed.

So far performed codoping of YAP:Pr prepared by micro-pulling down method did not manifest an evident improvement of the scintillation figure-of-merit even if the results achieved with the Hf codoping are encouraging. The codoping effect must both consistently and quantitatively balance possible material (non)stoichiometry and potential lack of oxygen in anion sublattice which could be the crucial issue in further technology optimization and improvement of YAP:Pr scintillation performance.

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