From Precursors to Ceramic Materials. II. Synthesis and Specific Features of New Garnet Structure Compounds

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In this paper, the sol-gel synthesis and characteristic properties of mixed-metal oxides Y₃ScₓAl₁₋ₓGaₓO₁₂ (0 ≤ x, y ≤ 5) having garnet crystal structure are reported. The polycrystalline powders were characterized by powder X-ray diffraction analysis (XRD), energy dispersive X-ray (EDX) analysis, IR spectroscopy and optical transmission measurements. Single-phase oxides Y₃ScₓAlₓGa₁₋ₓO₁₂, Y₃ScₓAlₓGa₂O₁₂, Y₃ScₓAl₀Ga₂O₁₂ and Y₃AlₓGa₂O₁₂ have been synthesized at 1000 °C. The transmittance spectra of Y₃ScₓAl₁₋ₓGaₓO₁₂ samples were measured at room temperature in the range of 200–1200 nm.

Keywords: YSAGG, mixed-metal garnets, substitution effects, optical materials.

INTRODUCTION

The use of aluminum compounds for electronic and optical applications shows an increased activity during past years. An important feature of metallic aluminum is the fact it auto-oxidizes to form a corrosion-resistant surface coating of alumina. Alumina is an unreactive thermally stable ceramics. There are several common forms of this material, each with its own set of unique applications [1]. Although the applications of aluminum oxides themselves are extensive, ternary systems, such as mullite, garnet, hibonite and β-alumina can offer advantages over those of the binary aluminum oxides [2–6].

The overall objective of the part of our research project is to search for advanced optical materials starting from low cost, air stable gel preceramic precursor [7–9]. To achieve this goal, recently the sol-gel method based on metal chelates in aqueous solvents has been developed to prepare pure and rare-earth doped yttrium aluminum garnet (YAG) [10, 11]. Moreover, the same sol-gel technique has been used for the synthesis of mettalumic oxides Y₅ScₓAlₓ₁₋ₓGaₓO₁₂ (0 ≤ x, y ≤ 5) (YSAGG), having complicated both chemical composition and garnet crystal structure [12–14]. We have demonstrated, that the sol-gel methods based on molecular precursors have a cutting edge over the other solution routes because they allow chemical interactions among the initial mixture of precursor species favoring the evolution of solid-state structure at the atomic level [15, 16].

The aim of this study was the evaluation of some specific features of different sol-gel derived mixed-metal garnets Y₅ScₓAlₓ₁₋ₓGaₓO₁₂. The paper describes the results concerning the synthesis, phase transformations, composition and optical properties of YSAGG compunds.

EXPERIMENTAL

Six samples Y₅ScₓAlₓ₁₋ₓGaₓO₁₂ (0 ≤ x, y ≤ 5) with different nominal composition, Y₅AlₓO₁₂ (YAG), Y₅ScₓAlₓGa₁₋ₓO₁₂ (YSAGG–212), Y₅ScₓAlₓGa₂O₁₂ (YSAGG–131), Y₅ScₓAlₓGa₂O₁₂ (YSAGG), Y₅AlₓGa₂O₁₂ (YSGG), Y₅ScₓGaₓO₁₂ (YSGG) were synthesized by aqueous sol-gel method. The gels were prepared according to the previously reported methodology [12]. The oven dried (110 °C) gel powders were ground in an agate mortar and preheated for 2 h at 800 °C in air. After an intermediate grinding in an agate mortar the powders were additionally sintered for 10 h at 1000 °C in air.

The synthesized samples were characterized by X-ray powder analysis (XRD) performed with a Siemens D-5000 powder diffractometer using CuKα1 radiation. The energy dispersive X-ray (EDX) analysis was performed, in vacuum, in the specimen chamber of an EDX coupled scanning electron microscope (SEM) CAM SCAN S4. The infrared (IR) spectra were recorded as KBr pellets on a BioRad FTIR–165 spectrometer. The optical transmission measurements of the garnet samples were carried out using SF-26 spectrophotometer at room temperature with a fused-quartz glass substrate inserted into the reference beam path of the spectrophotometer.

RESULTS AND DISCUSSION

The X-ray diffraction patterns for the calcined precursor gel powders and sintered for 10 h at 1000 °C are shown in Fig. 1. As seen, the samples fully crystallize, and the obtained phases slightly depend on the nominal composition of precursor gels. According to XRD analysis, sintering precursor gels at 1000 °C produced fully crystalline single-phase oxides Y₅ScₓAlₓGaₓO₁₂, Y₅ScₓAlₓGa₂O₁₂, Y₅ScₓAl₀Ga₂O₁₂ and Y₅AlₓGa₂O₁₂, which have well pronounced garnet crystal structure [7, 8, 10, 17, 18]. However, it is clear from Fig. 1 that the formation of Y₅ScₓGa₂O₁₂ garnet does not proceed under similar experimental conditions.

It is well known that in a crystalline garnet structure the cations are distributed among tetrahedral, octahedral and dodecahedral interstices [19]. The cations possibly may redistribute themselves, subject to the size of the individual ions, in order to stabilize the crystalline...
structure. We propose that such cationic distribution and the stabilization are related to a critical value of octahedral and dodecahedral radii (Al sites) where the substitution takes place. The cationic radii for the different compositions are listed in Table 1.

Table 1. The mean cationic radii at Al sites for the different $Y_3Sc_{x}Al_{25-x}Ga_{2}O_{12}$ compositions

<table>
<thead>
<tr>
<th>Garnet sample</th>
<th>Mean cationic radius (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_3Al_2O_12$ (YAG)</td>
<td>0.390</td>
</tr>
<tr>
<td>$Y_3Al_5Ga_2O_{12}$ (YAGG)</td>
<td>0.422</td>
</tr>
<tr>
<td>$Y_3Sc_2Al_5Ga_2O_{12}$ (YSAGG–131)</td>
<td>0.478</td>
</tr>
<tr>
<td>$Y_3Sc_2Al_5Ga_2O_{12}$ (YSAG)</td>
<td>0.534</td>
</tr>
<tr>
<td>$Y_3Sc_2Al_5Ga_2O_{12}$ (YSAGG–212)</td>
<td>0.566</td>
</tr>
<tr>
<td>$Y_3Sc_2Ga_5O_{12}$ (YSGG)</td>
<td>0.610</td>
</tr>
</tbody>
</table>

In view of the above, possible interpretation for the instability of the $Y_3Sc_2Ga_5O_{12}$ phase is that at this molar ratio the mean cationic radius of the composition (0.610 Angstroms) exceeds this critical value. The mean cationic radii for the phases forming a stable garnet structure are lower than the value observed for $Y_3Sc_2Ga_5O_{12}$. This shows that the further substitution of smaller Ga ions (0.47 Angstroms) through much larger Sc ions (0.75 Angstroms) causes the destabilization of the garnet structure. However, from the above discussions it is apparent that a systematic study of the small structural changes induced by Ga and Sc substitution in YAG should be performed.

Evidently, these XRD diffraction patterns show some negligible shift in the position of diffraction lines. This feature probably is caused by different unit size of garnet samples with different composition. It is well known that unit size is very much affected by variation of lattice parameters for substituted mixed-metal oxides [20, 21]. For the single-phase $Y_3Sc_{x}Al_{25-x}Ga_{2}O_{12}$ samples the most intensive (100 %) lines from the plane having Miller indices (420) are located in the range of $2\theta = 32.0° - 33.5°$ (see Fig. 1). It is known, that Bragg’s law treats X-rays as being diffracted from various sets of lattice planes and the Bragg diffraction angle, $\theta$, for each set is related to the $d$-spacing by Bragg’s law [22]. Fig. 2 shows the dependence of the calculated $d$-spacing of a set of (420) planes on the mean cationic radii at Al sites for the single-phase $Y_3Sc_{x}Al_{25-x}Ga_{2}O_{12}$ ceramic samples.

The random distribution of the results is seen indicating that no linear correlation between $d$-spacing and the mean cationic radius of the $Y_3Sc_{x}Al_{25-x}Ga_{2}O_{12}$ samples could be observed.

EDX analyses were also carried out on the single-phase $Y_3Sc_{x}Al_{25-x}Ga_{2}O_{12}$ samples. The EDX spectrum for $Y_3Al_2O_{12}$ sample is shown presented in Fig. 3.

Fig. 3. Energy dispersive X-ray spectrum of $Y_3Al_2O_{12}$ ceramic sample

From Fig. 3 is evident that only yttrium, aluminium and oxygen are present in the sample, and no other elements can be detected from the EDX spectrum. These results confirm that synthesized YAG sample is of high purity and good quality. The EDX spectra of two representative YSAGG ceramic samples ($Y_3Sc_2Al_5Ga_2O_{12}$ and $Y_3Sc_2Al_5Ga_2O_{12}$) are presented in Figs. 4 and 5, respectively.
The appearance of scandium and gallium in the EDX spectra of both YSAGG samples is evident. Besides, Fig. 5 shows that intensity of Al line increases as compared with one in Fig. 4 and intensities of Sc and Ga lines decrease. These changes in the intensities of Al, Sc and Ga lines are in a good agreement with the chemical composition of investigated ceramic samples. Finally, EDX analyses of the synthesized Y₃ScₓAl₅₋ₓ₋ₓGaₓO₁₂ samples showed that the content of metals in the separate crystallites corresponds to the nominal composition of starting materials, i.e. the syntheses yielded monophasic and homogeneous mixed-metal garnet samples.

IR spectra of calcined for 8 h at 1000°C single-phase Y₃ScₓAl₅₋ₓ₋ₓGaₓO₁₂ samples were obtained as well (Figs. 6 and 7).

A broad band at 3400 cm⁻¹ which remains almost unchanged for different garnet samples can be assigned to the adsorbed water during the exposure of dried powder to air [8, 23]. The several intense bands in the range 900 – 450 cm⁻¹ are characteristic of the metal-oxygen vibrations in the ceramic samples. According to Vaqueiro and Lopez-Quintela [8, 24] these bands are characteristic of YAG structure and attributable to the stretching mode of the tetrahedral units in the garnet structure.

It is interesting to note that the observed characteristic stretching frequencies also are slightly shifted for different garnet compounds. Fig. 8 shows the dependence of the position of the first M–O peaks presented in all IR spectra of Y₃ScₓAl₅₋ₓ₋ₓGaₓO₁₂ samples on the mean cationic radii at Al sites.

As seen from Fig. 8, wavenumber, consequently and frequency of the characteristic M–O vibrations in Y₃ScₓAl₅₋ₓ₋ₓGaₓO₁₂ garnet samples decreases almost
samples were measured at room temperature in the range of 200 – 1200 nm. Fig. 9 demonstrates the transmission spectrum of Y3Sc2Al5Ga2O12 ceramic sample produced by sol-gel method.

The transmittance spectra of Y3ScAl5-x-yGa2O12 samples were measured at room temperature in the range of 200 – 1200 nm. Fig. 9 demonstrates the transmission spectrum of Y3Sc2Al5Ga2O12 ceramic sample produced by sol-gel method.

As seen from Fig. 9, the absorption edge for the Y3Sc2Al5Ga2O12 sample could be detected at ~210 nm. In UV range the garnet sample shows a significant decrease of transmission, which is required for optical materials [25 – 28]. In the higher wavelength region the transmission is almost constant, i.e. not wavelength dependent. Such garnet compound doped by rare-earth element would have an excellent optical quality [29].

Fig. 10 shows optical transmission spectrum of Y3Sc2Al5Ga2O12 ceramic sample.

As seen, the transmittance of Y3Sc2Al5Ga2O12 is slightly higher than that of Y3ScAl5Ga2O12. Also, the absorption edge for the Y3Sc2Al5Ga2O12 is slightly shifted to the higher wavelength (~220 nm). Interesting fact is, that the recorded transmission spectrum for Y3Sc2Al5Ga2O12 compound was found to be almost identical as for Y3ScAl5Ga2O12. It seems that intensity of transmittance and position of absorption edge correlate with the amount of scandium in the garnet. On the other hand, this can be attributed to the difference in the grain growth in the specimens [30]. However, the

transmittance of Y3Al2O12 and Y3Al2Ga2O12 samples was significantly lower to compare with those scandium-containing garnets. Moreover, the absorption edges for YAG and YAGG are located in low UV region (<200 nm). Therefore we can suggest that with increasing amount of scandium in the mixed-metal garnets the higher transmittance and negligible shift in the absorption edge position are observed. These physical features, however, are independent on the amount of gallium in the investigated samples. Finally, high phase purity, good mechanical properties, broad transparent range of Y3Sc2Al5-x-yGa2O12 garnets make them an excellent candidates of host materials for advanced optical applications [31, 32].

CONCLUSIONS

Mixed-metal oxides Y3ScAl5-x-yGa2O12 (0 ≤ x, y ≤ 5) with different nominal composition were synthesized by aqueous sol-gel method. Sintering gels at 1000 °C produced fully crystalline single-phase compounds Y3ScAl5Ga2O12, Y3ScAl5Ga2O12, Y3Sc2Al5O12, and Y3Al2Ga2O12, with well pronounced garnet crystal structure. The XRD diffraction patterns showed negligible shift in the position of diffraction lines. The calculated d-spacing of a set of (420) planes, however, did not correlate with the mean cationic radii at Al sites for the single-phase Y3ScAl5-x-yGa2O12 samples. It was determined that the frequency of the characteristic M-O vibrations in Y3ScAl5-x-yGa2O12 garnet samples decreased almost linearly with increasing the mean cationic radius at Al sites. Such phenomenon was never observed previously in mixed-metal oxides, to our knowledge. The optical transmittance spectra showed that transmission and absorption edge position are slightly dependent on the amount of scandium in the mixed-metal garnets.

REFERENCES


