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Structure and transport properties of melt grown Sc_2O_3 and CeO_2 doped ZrO_2 crystals



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ABSTRACT

In this work we report a study of $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ solid solution crystals (x = 0.08–0.10; y = 0.005–0.015) grown by skull melting technique. The crystal structure of the material was studied using X-ray diffraction, Raman spectroscopy and impedance spectroscopy. The study showed that optically homogeneous and transparent crystals cannot be grown from the melt in the experimental composition range. For overall stabilizing oxide concentrations of above 10 mol% the crystals contained a cubic phase and a rhombohedral one, whereas at concentrations of lower than 10 mol% a cubic and a tetragonal phases coexisted. Ceria introduction into the $(ZrO_2)_{1-x}(Sc_2O_3)_x$ system increases its high-temperature ionic conductivity. The highest ionic conductivity was observed in 0.5 mol% ceria containing crystals.

1. Introduction

Zirconia based materials find general application as solid electrolytes for solid oxide fuel cells [1,2]. An important practical task is the development of new materials having highest ionic conductivity aimed at reducing the working temperature of solid electrolytes thus increasing their service life, simplifying the design and reducing the cost of the materials used for the fabrication of solid oxide fuel cells.

Scandia (ScSZ) stabilized zirconia base ceramics have the highest conductivity at moderate temperatures [3]. However, a major disadvantage of these materials is the degradation of their conductivity during long-term operation due to an unstable phase composition. The materials with the highest conductivity in the $ZrO_2-(10-12)$ mol% Sc_2O_3 composition range exhibit a transition from the cubic to the rhombohedral phase accompanied by a significant decrease in the conductivity [3,4]. Partial replacement of scandia for other oxides in the ZrO_2 - Sc_2O_3 system aimed at increasing the stability of the highconductivity cubic phase proves to be one of the most efficient solutions to these problems [5]. Many researchers modify the electrolyte structure by introducing, along with scandia rare-earth or other metal oxides [6–13]. Of these materials, scandia and ceria co-stabilized zirconia based ones currently attract increasing attention [9–13]. From this viewpoint, one of the most attractive systems which have a high ionic conductivity at 700–900 °C is the Sc_2O_3 - CeO_2 - ZrO_2 one. For example, the $10Sc_2O_3$ -90ZrO₂ ceramics co-doped with $1 \mod \%$ CeO₂ have an ionic conductivity of 16.7 mS/cm at 600 °C [7]. A number of studies have been devoted to the investigation of the physicochemical and transport properties of materials of this system [8–13]. Noteworthy, the ionic conductivity of ceramics having the same chemical composition depends largely on their phase composition, microstructure, density and other parameters which in turn depend on the material synthesis technology [14–17]. For example, the total ionic conductivity.

The aim of this work is to synthesize Sc_2O_3 -CeO₂-ZrO₂ crystals and to study their structure and physicochemical properties, including the transport ones. As shown earlier, the total conductivity of these crystalline materials only depends on their bulk conductivity even if a twin structure is present [17]. Thus, the study of the transport properties of the crystals will provide information on the contribution of the bulk conductivity component of the solid electrolyte excluding the contribution of the grain boundary conductivity, in order to simplify the analysis of ionic conductivity mechanisms.

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2. Experimental

 $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ solid solution crystals (x = 0.08-0.10; y = 0.005-0.015) were grown by the directional melt crystallization in a cold crucible technique [14]. $(ZrO_2)_{1-x}(Sc_2O_3)_x$ crystals (x = 0.08-0.10) were synthesized for reference.

The scandia and ceria distributions along the crystals were studied under a JEOL 5910 LV scanning electron microscope with an INCA Energy dispersive attachment. The reference specimens used for the crystal composition analysis were molten zirconia, scandia and ceria. The phase analysis was conducted using X-ray diffraction on a Bruker D8 diffractometer in CuK α radiation and Raman spectroscopy. The excitation source was a 532 nm laser. The structure of the crystals was studied under a JEM 2100 microscope at a 200 keV acceleration voltage.

The density was measured by hydrostatic weighing on a Sartorius hydrostatic weighing instrument. The microhardness of the crystals was measured on a DM 8 B AUTO microhardness tester with a 50 g load.

The conductivity of the zirconia based crystals was measured in the 400–900°C temperature range with a Solartron SI 1260 frequency characterizing device in the 1 Hz to 5 MHz range with a 24 mV AC voltage signal. The test wafers were $7 \times 7 \text{ mm}^2$ in size and 0.5 mm thick. The electric contacts were formed by applying platinum paste on the opposite sides of the crystals by burning-in at 950 °C for 1 h in air. The impedance spectra were processed using the ZViewv. 2.8 software. The conductivity of the crystals was calculated based on the data derived from the impedance spectra taking into account the size of the specimens.

3. Results and discussion

Table 1 shows the notations, composition, density and microhardness of the synthesized crystals.

Fig. 1 shows the appearance of the 8Sc1CeSZ, 9Sc1CeSZ and 10Sc1CeSZ crystals. The crystals were semitransparent and opalescent, without cracks, and their shape and sizes were similar to those of the scandia and/or yttria stabilized zirconia crystals [18,19]. The optical inhomogeneities of the crystal microstructure that can be seen in the images are caused by the differences in the phase composition of the crystals which will be discussed below.

The color of the ceria stabilized crystals was inhomogeneous, varying from colorless to dark-orange. The inhomogeneous color can be attributed to the variation of the valence state of the cerium ion during the post-growth cooling of the crystal and to the fluctuation of the ceria concentration during crystallization. The former factor shows itself in a reduction of the color intensity up to the appearance of colorless regions on the crystal surface, this being primarily typical of crystals growing close to the peripheral regions of the crystallizing ingot. This a change in color indicates a decrease in the concentration of Ce³⁺ cations the absorption bands of which are located in the visible range and impart orange color to the growing crystals [20]. The Ce³⁺ \rightarrow

Ce4+ transition occurs during ingot cooling due to oxygen diffusion from the periphery to the center of the ingot. Air annealing of the crystals at 400-1200 °C eliminates the color inhomogeneity and produces colorless crystals. Vacuum annealing at 1200-1400 °C leads to the $Ce^{4+} \rightarrow Ce^{3+}$ transition and hence produces the homogeneous color of the crystals, ranging from orange to dark-red depending on the ceria content in the crystal [20]. The inhomogeneous crystal color showing itself in the formation of regions or strips with different color intensities is caused by ceria segregation toward the top part of the ingot due to the less than unity effective cerium distribution coefficient [20]. This local increase in the ceria concentration disturbs the normal crystallization process and accelerates the crystallization of the region enriched with the displaced impurity due to the constitutional supercooling at the crystallization front. Energy dispersive X-ray study of the scandia and ceria distributions along the crystals showed that the intense colored strips which are typically located in the top part of the crystals may contain 1.5-2 higher ceria compared with the homogeneously colored crystal regions.

Therefore the specimens used for studying the crystal structure and transport properties were cut from the crystal regions which did not contain strips with elevated cerium concentrations or growth defects typical of constitutional supercooling (cellular structure, inclusions, bubbles etc.) [20]. We could not synthesize optically homogeneous and transparent $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ crystals in the experimental composition range, unlike scandia and yttria stabilized crystals grown using the same method [21].

The phase composition of the crystals was studied with X-ray diffraction and Raman spectroscopy. Table 2 summarizes X-ray data on the phase composition and lattice parameters of the crystals and data on the lattice parameters of the crystals annealed in air at 1200 °C for 2 h.

According to the phase analysis data, the 8Sc1CeSZ, 8ScSZ and 9ScSZ crystals are single-phase and tetragonal. Analysis of the lattice parameters of the tetragonal 8Sc1CeSZ and 8ScSZcrystals shows that ceria addition increases the lattice parameter *a* and reduces the lattice parameter *c*. The change of the lattice parameter *c* is greater than that of the lattice parameter *a*, this leading to a decrease in the tetragonality $(c/\sqrt{2}a)$ of the 8Sc1CeSZ crystals. As a result the structure of the 8Sc1CeSZ crystals becomes closer to cubic than that of 8ScSZ. The data shown in Table 2 suggest that a decrease in the concentration of the Ce³⁺ cations after air annealing changes the structural parameters of the 8Sc1CeSZ crystal. Air annealing of the 8Sc1CeSZ crystals increases the tetragonality of their lattice. The as-annealed 8Sc1CeSZ crystal lattice parameters are almost the same as those of the 8ScSZ crystal. This behavior can be attributed to a decrease in the atomic radius of cerium due to Ce³⁺ ion oxidation to Ce⁴⁺, their atomic radii being 1.143 and 0.97 Å, respectively [22]. Furthermore, this transition is accompanied by a decrease in the number of vacancies because Zr⁴⁺ ion substitution for Ce⁴⁺ in the lattice does not require charge compensation.

Along with the tetragonal phase the 8.5Sc0.5CeSZ crystal contains a

Table 1

Composition, density and microhardness of the synthesized crystals.

Notation	Composition	Density, g/cm ³	HV Microhardness, kgf/mm ²
8ScSZ	(ZrO ₂) _{0.92} (Sc ₂ O ₃) _{0.08}	5.862 ± 0.004	1610 ± 20
9ScSZ	$(ZrO_2)_{0.91}(Sc_2O_3)_{0.09}$	5.807 ± 0.001	1640 ± 20
8Sc1CeSZ	(ZrO ₂) _{0.91} (Sc ₂ O ₃) _{0.08} (CeO ₂) _{0.01}	5.850 ± 0.003	1660 ± 20
8.5Sc0.5CeSZ	(ZrO ₂) _{0.91} (Sc ₂ O ₃) _{0.085} (CeO ₂) _{0.005}	5.776 ± 0.002	1570 ± 50
8.5Sc1.5CeSZ	(ZrO ₂) _{0.90} (Sc ₂ O ₃) _{0.085} (CeO ₂) _{0.015}	5.787 ± 0.001	1560 ± 50
9Sc1CeSZ	(ZrO ₂) _{0.90} (Sc ₂ O ₃) _{0.09} (CeO ₂) _{0.01}	5.791 ± 0.004	1680 ± 20
9.5Sc0.5CeSZ	(ZrO ₂) _{0.90} (Sc ₂ O ₃) _{0.095} (CeO ₂) _{0.005}	5.778 ± 0.004	1585 ± 50
9.5Sc1CeSZ	(ZrO ₂) _{0.895} (Sc ₂ O ₃) _{0.095} (CeO ₂) _{0.01}	5.763 ± 0.003	1690 ± 60
10Sc0.5CeSZ	(ZrO ₂) _{0.895} (Sc ₂ O ₃) _{0.1} (CeO ₂) _{0.005}	5.738 ± 0.001	1695 ± 30
10Sc1CeSZ	(ZrO ₂) _{0.89} (Sc ₂ O ₃) _{0.10} (CeO ₂) _{0.01}	5.757 ± 0.004	1720 ± 20
10ScSZ	(ZrO ₂) _{0.89} (Sc ₂ O ₃) _{0.10}	5.763 ± 0.002	$1580~\pm~20$



Fig. 1. Appearance of the 8Sc1CeSZ (a), 9Sc1CeSZ (b) and 10Sc1CeSZ (c) crystals. Insets: optical microstructure images in transmission mode for 1 mm thick polished wafers (×25).

small quantity of the cubic phase. Annealing of this crystal also increases the tetragonality, with the cubic phase being retained in the lattice. Comparison of the 8Sc1CeSZ and 8.5Sc0.5CeSZ crystals having the same overall concentration of the stabilizing oxides, i.e. 9 mol%, suggests that an increase in the scandia content and a decrease in the ceria content reduce the tetragonality and the formation of the cubic

phase.

The 8.5Sc1.5CeSZ, 9Sc1CeSZ and 9.5Sc0.5CeSZ specimens with an overall stabilizing oxide concentration of 10 mol% contain two phases: the tetragonal one and the cubic one. Scandia substitution by ceria in this batch of crystals reduces the lattice parameter c of the tetragonal phase and the tetragonality. The lattice parameters of the cubic phase in

Table 2

X-ray	data on p	phase com	position ar	d lattice	parameters	of test of	rystals	before	and	after	air	annealing	at 1	200	Ć.
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Specimen	Phase composition	Weight fraction, %	Lattice parameter							
			As-grown			As-annealed				
			a, nm	c, nm	c/√2 a	a, nm	c, nm	c/√2 a		
8ScSZ	t	100 (5)	0.3596(1)	0.5123(1)	1.007	0.3596(1)	0.5123(1)	1.007		
9ScSZ	t	100 (5)	0.3595(1)	0.5122(1)	1.007	0.3595(1)	0.5122(1)	1.007		
8Sc1CeSZ	t	100 (5)	0.3599(1)	0.5114(1)	1.005	0.3597(1)	0.5123(1)	1.007		
8.5Sc0.5CeSZ	t	80 (5)	0.3596(1)	0.5106(1)	1.004	0.3598(1)	0.5117(1)	1.006		
	с	20 (5)	0.5091(1)			0.5091(1)				
8.5Sc1.5CeSZ	t	80 (5)	0.3597(1)	0.5112(1)	1.005	0.3596(1)	0.5112(1)	1.005		
	с	20 (5)	0.5092(1)			0.5092(1)				
9Sc1CeSZ	t	85 (5)	0.3597(1)	0.5110(1)	1.005	0.3597(1)	0.5111(1)	1.005		
	с	15 (5)	0.5092(1)			0.5092(1)				
9.5Sc0.5CeSZ	t	80 (5)	0.3597(1)	0.5109(1)	1.004	0.3597(1)	0.5110(1)	1.004		
	с	20 (5)	0.5092(1)			0.5092(1)				
9.5Sc1CeSZ	t	65 (5)	0.3597(1)	0.5101(1)	1.003	0.3597(1)	0.5101(1)	1.003		
	с	20 (5)	0.5092(1)			0.5092(1)				
	r	15 (5)	0.3561(2)	0.9008(2)		0.3561(2)	0.9008(2)			
10Sc0.5CeSZ	r	85 (5)	0.3560(2)	0.9007(2)		0.3560(2)	0.9007(2)			
	с	15 (5)	0.5092(1)			0.5092(1)	0.5092(1)			
10Sc1CeSZ	с	70 (5)	0.5093(1)			0.5093(1)				
	r	30 (5)	0.3560(1)	0.9007(2)		0.3560(2)	0.9007(2)			
10ScSZ	с	75 (5)	0.5091(1)			0.5091(1)				
	r	25 (5)	0.3562(1)	0.9010(2)		0.3562(2)	0.9010(2)			

Where c is the cubic Sc_2O_3 doped ZrO_2 phase,

t is Sc₂O₃ doped ZrO₂ tetragonal phase.

r is Sc_2O_3 doped ZrO_2 rhombohedral phase.

different crystals change but slightly, within the measurement error. Annealing of the crystals does not change the tetragonality of the tetragonal phase and the lattice parameter of the cubic phase.

The rhombohedral phase forms at an overall stabilizing oxide concentration of 10.5 mol% in the 9.5Sc1CeSZ and 10Sc0.5CeSZ crystals. The 9.5Sc1CeSZ crystal contains three phases: the tetragonal, the cubic and the rhombohedral ones, with the tetragonal and cubic phases prevailing. The 10Sc0.5CeSZ crystal contains two zirconia phases, i.e. the rhombohedral and the cubic ones, with the tetragonal phase content being far higher than the cubic phase content.

The 10Sc1CeSZ crystal contains two phases, i.e. the cubic and the rhombohedral ones, with the cubic phase prevailing in the bottom part of the crystal and the rhombohedral one, in the top part of the crystal. An increase of the ceria content in the 10Sc1CeSZ crystal as compared with the 10Sc0.5CeSZ one leads to an increase in the content of the cubic phase but does not provide for the formation of a single-phase cubic crystal. Due to the higher ionic radius of Ce⁴⁺ compared with that of Zr⁴⁺ the lattice parameter of the cubic phase in the 10Sc1CeSZcrystal is greater than that in the 10Sc0.5CeSZ and 10ScSZ crystals.

To assess the phase stability of the crystals to mechanical impact we carried out phase analysis for powdered crystals. The phase composition change caused by crystal grinding was observed in crystals having an overall stabilizing oxide concentration of above 10 mol%. In the 9.5Sc1CeSZ crystal the cubic phase transformed to the rhombohedral one as a result of grinding. In the 10Sc0.5CeSZ and 10Sc1CeSZ crystals containing a mixture of the cubic and the rhombohedral phases, the quantity of the rhombohedral phase increased after grinding. The formation of the more thermodynamically stable rhombohedral phase in the as-grinded two-phase crystals may be favorable for the transition of the less stable cubic phase to the rhombohedral one. These results agree with earlier data [23]. For example, the ZrO₂ samples co-doped with 10 mol% Sc₂O₃ and 1 mol% CeO₂ exhibited the formation of the straininduced rhombohedral phase in a thin region near the free surface of the sample. The cubic to rhombohedral transition was also observed in grinded ZrO₂ samples doped with 10.5 mol% Sc₂O₃ [24].

Analysis of the phase composition data for the crystal specimens suggests that for an overall stabilizing oxide concentration of above 10 mol% the crystals contain the rhombohedral phase along with the cubic one, while at an overall concentration of below 10 mol% the cubic and the tetragonal phases coexist.

Fig. 2 shows TEM images of the 10ScSZ, 10Sc0.5CeSZ and 10Sc1CeSZ crystals that contain the rhombohedral phase.

In the 10ScSZ crystal the rhombohedral phase is in the form of elongated inclusions in the cubic matrix. These inclusions are distributed homogeneously in the entire crystal bulk. The 10Sc0.5CeSZ crystal which consists mainly of the rhombohedral phase contains large twins typical of the rhombohedral phase. The boundary between the cubic phase and the large twins of the rhombohedral phase can be seen in Fig. 2(c). It should be noted that unlike the 10ScSZ crystal the large rhombohedral phase in the 10Sc1CeSZ crystal are distributed inhomogeneously along its length and concentrate mainly in the top part of the crystal.

Thus, single-phase cubic crystals could not be synthesized for the test composition range. Our phase composition data disagree with the data of many earlier works for specimens synthesized by various ceramic technologies. For example, the 10Sc1CeSZ [7,9,10,14,15] and 9Sc1CeSZ [8,13,25] ceramic specimens were reported to have a single-phase cubic structure. The phase composition and properties of the zirconium base materials depend largely on thermal history. For ceramic technologies the materials are typically sintered at up to 1600 °C. We synthesized the crystals by directional melt crystallization beginning from temperatures above the melting point (approx. 2800 °C). This difference in the synthesis conditions may alter the phase formation mechanisms occurring in the material and eventually lead to different phase compositions of the synthesized specimens in spite of their similar chemical composition.

We also studied the phase composition of the crystals using Raman spectroscopy. Fig. 3 shows the Raman spectra of the test crystals.

The Raman spectra of the 8Sc1CeSZ crystals are typical of the tetragonal phase [26,27]. The Raman spectra of the 8.5Sc0.5CeSZ, 8.5Sc1.5CeSZ, 9Sc1CeSZ and 9.5Sc0.5CeSZ crystals differ from the typical spectral pattern of the tetragonal phase. The difference is that the tetragonal phase bands are wider and less intense. Furthermore, the 638 cm^{-1} band shifts toward lower frequencies. This change in the Raman spectra can be caused by an increase in the Zr–O bond strength and the presence of the cubic phase in these crystals [26]. A similar evolution of the Raman spectra of the 10ScSZ specimens doped with 0.5–5 mol% CeO₂ was observed earlier [28]. The Raman spectra of the 10Sc0.5CeSZ crystals contain mainly the bands of the rhombohedral phase which differ significantly from those of the cubic and the tetragonal phases [27,29]. The 10Sc1CeSZ crystals contain the cubic and the rhombohedral phases. Thus, the Raman data on the phase composition of the crystals is in a good agreement with the X-ray diffraction data.

The density of the crystals is controlled by their chemical and phase compositions and porosity, the latter being zero for the synthesis technique used. The densities shown in Table 1 agree well with the variation of the phase composition in the crystals. The tetragonal 8Sc1CeSZ crystals have the highest density. The density of the two-phase crystals containing the tetragonal and the cubic phases decreases with an increase in the quantity of the cubic phase. The densities of the solid solutions having an overall stabilizing oxide concentration of above 10 mol% depend on the content of the rhombohedral phase. Therefore, the lowest density was observed in the 10Sc0.5CeSZ crystal which mainly contained the rhombohedral phase.

All the test crystals have high microhardness and low fracture



Fig. 2. TEM images of the 10ScSZ (a), 10Sc0.5CeSZ (b) and 10Sc1CeSZ (c). Insets: electron diffraction patterns of the respective crystal regions.



Fig. 3. Raman spectra of the $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ crystals.

toughness. With the ceria concentration being equal, the microhardness of the crystals grows with scandia concentration.

Fig. 4 shows the conductivity of the test crystals as a function of temperature in Arrhenius coordinates. The conductivity vs temperature curves of the 10Sc0.5CeSZ and 10ScSZ crystals exhibit clear bends at 550–650 °C caused by the rhombohedral to cubic phase transition. The curves of the 9.5Sc1CeSZ and 10Sc1CeSZ crystals do not have that bend, possibly because of the low content of the rhombohedral phase in these specimens and an inhomogeneous distribution of the rhombohedral phase along the crystals. As an example, Fig. 5 shows impedance spectra of the crystals for 10Sc0.5CeSZ and 10ScSZ.

Fig. 6 shows the conductivities of the $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ solid solutions of all the test compositions at 1173 K as a function of the Sc_2O_3 content.

It can be seen from Fig. 6 that ceria doping increases the conductivity of the crystals for all the test compositions, and with the ceria content being constant the conductivity of the crystals increases gradually with scandia concentration. The lowest conductivity for the test composition range was observed in the single-phase tetragonal 8ScSZ, 9ScSZ and 8Sc1CeSZ crystals.

Ceria addition in an amount of 1 mol% to the $(ZrO_2)_{1-x}(Sc_2O_3)_x$ system increases the conductivity of the material the most significantly in the crystals containing 9 mol% Sc₂O₃. This can be accounted for by



Fig. 4. Conductivity vs temperature functions of the $(ZrO_2)_{1-x}(Sc_2O_3)_x$ and $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ crystals.



Fig. 5. Impedance spectra of the 10Sc0.5CeSZ and 10ScSZ crystals.



Fig. 6. Conductivity of the $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ solid solutions at 1173 K as a function of Sc_2O_3 content.

changes in the crystal structure, i.e., with the formation of a two-phase c + t structure and a decrease of the tetragonality of the tetragonal phase. If 1 mol% ceria is added to the 8ScSZ and 10ScSZ crystals the crystal lattice parameters change although the phase composition remains the same.

Thus, 1 mol% ceria co-doping of the ScSZ crystals increases the conductivity of the crystals, but the highest conductivity in the test composition range occurs for 0.5 mol% ceria doping of the solid solutions. The conductivity of the material was also reported to decrease with an increase in the ceria concentration from 0 to 1 mol% in $[(ZrO_2)_{1-x}(CeO_2)_x]_{0.89}(Sc_2O_3)_{0.11}$ ceramic specimens [30].

In fact, the presence of the electronic component of the conductivity is possible in ceria-containing ZrO_2 systems at high temperatures. However, as shown earlier [31], the contribution of the electron conductivity to the total conductivity of $[(ZrO_2)_{1-x}(CeO_2)_x]_{0.92}(Y_2 O_3)_{0.08}$ for x = 0.1 sample at 1000°C and an oxygen pressure of 1 atm is negligible. The ceria content in the crystals did not exceed 1.5 mol%. Thus, it can be assumed that the measured total conductivity is ionic.

Generally, the bulk conductivity of the material depends, along with its phase composition, on a number of additional factors which control the mobility of the oxygen ions. These factors include the formation of different types of defect complexes, lattice stress due to the difference in the ionic radii in the cation sublattice and the variable valence of the cerium ions which may be present in different states, i.e., Ce^{4+} or Ce^{3+} .

4. Summary

 $(ZrO_2)_{1-x-y}(Sc_2O_3)_x(CeO_2)_y$ solid solution crystals (x = 0.08–0.10; y = 0.005–0.015) were for the first time grown by directional crystallization from the melt.

We show that melt synthesis in the test composition range does not allow growing optically homogeneous and transparent crystals. At an overall stabilizing oxide concentration of above 10 mol% the crystals contain the cubic and the rhombohedral phases, and at an overall concentration of below 10 mol% the cubic and the tetragonal phases are present.

Ceria addition to the $(ZrO_2)_{1-x}(Sc_2O_3)_x$ system increases the hightemperature ionic conductivity of the material, and with the ceria content being constant the conductivity of the crystals increases gradually with scandia concentration. The lowest conductivity for the test composition range was observed in the single-phase tetragonal 8ScSZ, 9ScSZ and 8Sc1CeSZ crystals. The decrease of the ceria concentration from 1.0 to 0.5 mol% leads to an increase in the high-temperature conductivity of the crystals in the entire test composition range. The highest conductivity was observed in the 10Sc0.5CeSZ crystals, yet they contained a lot of rhombohedral phase.

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