Improved oxide-ion conductivity of NdBalnO₄ by Sr doping†

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The oxide-ion conductivity of NdBalnO₄ has been increased by Sr doping. Nd₀.₉Sr₀.₁BalnO₄₋₀.₉₅ showed the highest electrical conductivity among Nd₁₋ₓSrₓBalnO₄₋ₓ/₂ (x = 0.0, 0.1, 0.2, and 0.3). The oxide-ion conductivity σion of Nd₀.₉Sr₀.₁BalnO₃₋₀.₉₅ (σion = 7.7 × 10⁻⁴ S cm⁻¹) is about 20 times higher than that of NdBalnO₄ (σion = 3.6 × 10⁻⁵ S cm⁻¹) at 858 °C, and the activation energy of oxide-ion conduction is a little lower for Nd₀.₉Sr₀.₁BalnO₃₋₀.₉₅ (0.795(10) eV) than that for NdBalnO₄ (0.91(4) eV). The structure analysis based on neutron powder diffraction data revealed that the Sr exists at the Nd site and oxygen vacancies are observed in Nd₀.₉Sr₀.₁BalnO₃₋₀.₅. This result indicates that the increase of the oxide-ion conductivity is mainly due to the increase of the carrier concentration. The bond valence-based energy landscape indicated two-dimensional oxide-ion diffusion in the (Nd,Sr)₂O₃ unit on the bc-plane and a decrease of the energy barrier by the substitution of Nd with Sr cations.

Introduction

Oxide-ion conductors, which include pure ionic conductors and mixed oxide-ion and electronic conductors, attract significant interest because of their varied uses in oxygen separation membranes and cathodes for solid-oxide fuel cells (SOFCs).¹

The oxide-ion conductivity is strongly dependent on the crystal structure and particularly the defects. At present, several structures, such as fluorites,²,³ perovskites,²,⁴ K₂NiF₄,²,⁵ melilitites,²,⁶ and apatites,²,⁷ are known to show high oxide-ion conductivities. Further development of oxide-ion conductors involves investigating materials with new types of structures. Recently, we have discovered a new structure family of oxide-ion conductors based on NdBalnO₄, a monoclinic P2₁/c perovskite-related phase with a layered structure.⁸ In this study, we have successfully improved the oxide-ion conductivity of NdBalnO₄ by Sr doping at the Nd site, which aims to increase the concentration of oxygen vacancies (i.e., carriers for the oxide-ion conduction) and to lower the activation energy by exchanging Nd³⁺ with the larger Sr²⁺ cation. This study reports on the electrical conductivity and the crystal structure of Sr-doped NdBalnO₄. The electrical conductivity of NdBalnO₄ was also investigated again for comparison.

Experimental section

Synthesis and characterization of the chemical composition

Nd₁₋ₓSrₓBalnO₄₋ₓ/₂ (x = 0.0, 0.1, 0.2, 0.3, and 0.4) compounds were synthesized by solid-state reactions. Nd₂O₃ (99.95% purity) and BaCO₃ (99.99% purity) from Kanto Chemical Co. Inc., SrCO₃ and In₂O₃ (both 99.9% purity) from Kojundo Chemical Lab. Co., Ltd. were accurately weighed in 1 – x : 1 : x : 1 cation molar ratios, and they were mixed and ground using a planetary ball mill (Fritsch, P7) for 30 min. The mixtures were calcined at 1000 °C for 8 h in air for decarbonization. Then, the calcined mixtures were milled again for 30 min and uniaxially pressed into pellets at about 50 MPa. These pellets were sintered in air at 1400 °C for 24 h.

The cation ratio of Nd₀.₉Sr₀.₁BalnO₃₋₀.₅ was confirmed by inductively coupled plasma optical emission spectrometry (ICP-OES) as Nd : Sr : Ba : In = 0.919(8) : 0.0996(9) : 0.992(3) : 0.899(9), which agreed with the average chemical composition of the starting mixture, Nd : Sr : Ba : In = 0.9 : 0.1 : 1.1 within 3σ. Here, the σ is the standard deviation of the measured chemical composition and the number in the parenthesis is the last digit of σ.

Thermogravimetric analyses (TGA) of NdBalnO₄ and Nd₀.₉Sr₀.₁BalnO₃₋₀.₅ in Ar flow (50 mL min⁻¹) were conducted using a Bruker-AXS TG-DTA2020S instrument with heating and cooling rates of 10 °C min⁻¹. The TG measurements were repeated three times to confirm the reproducibility and minimize artefacts from adsorbed species such as water.
Electrical conductivity measurements

The electrical conductivities of Nd$_{1-x}$Sr$_x$BaInO$_{4-x/2}$ ($x = 0.0, 0.1, 0.2, 0.3$) were measured using a DC 4-probe method using sintered pellets (ca. 4.4 mm $\phi \times 30$ mm with densities in the range of 90–95% of theoretical density) with Pt electrodes over the temperature range from 400 °C to 1200 °C in air. The oxygen partial pressure $P(O_2)$ dependence of the electrical conductivities of NdBaInO$_4$ and Nd$_{0.5}$Sr$_{0.5}$BaInO$_{3.95}$ was measured at 858 °C using N$_2$/H$_2$, N$_2$/CO$_2$, and N$_2$/O$_2$ gas mixtures. The $P(O_2)$ was monitored by an oxygen sensor that was set close to the sample. The oxide-ion conductivities of NdBaInO$_4$ and Nd$_{0.5}$Sr$_{0.5}$BaInO$_{3.95}$ were measured from 610 °C to 1100 °C under $P(O_2) = 3.6 \pm 2.6 \times 10^{-12}$ atm for NdBaInO$_4$ and $P(O_2) = 8.8 \pm 6.2 \times 10^{-14}$ atm for Nd$_{0.5}$Sr$_{0.5}$BaInO$_{3.95}$.

Neutron and synchrotron X-ray diffraction measurements

Synchrotron X-ray powder diffraction (XRPD) measurements were conducted using a Debye–Scherrer camera with an imaging plate on beam line BL19B2 at SPring-8 (27 °C; wavelength = 0.399662(2) Å). Room temperature time-of-flight (TOF) neutron powder diffraction (NPD) measurements (24 °C) were performed using the IMATERIA diffractometer at the J-PARC facility, Tokai, Japan. High-temperature angle dispersive-type NPD measurements (800 °C using a vacuum furnace; wavelength = 1.83432(4) Å) were performed using a neutron powder diffractometer HRPD installed at HANARO reactor, KAERI, Korea.

Results and discussion

XRPD patterns of Nd$_{1-x}$Sr$_x$BaInO$_{4-x/2}$ ($x = 0.0, 0.1, 0.2, 0.3$ and 0.4) identified the final products to be the monoclinic $P2_1/c$ NdBaInO$_4$ phase, except $x = 0.4$, which showed a different XRPD pattern with additional peaks, indicating possible saturation of the dopant within the NdBaInO$_4$ structure (Fig. 1a). We found that the total electrical conductivity of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ is higher than that of NdBaInO$_4$, Nd$_{0.8}$Sr$_{0.2}$BaInO$_{3.9}$, and Nd$_{0.7}$Sr$_{0.3}$BaInO$_{3.85}$ (Fig. 1b). Therefore, we focused on the Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ composition for further detailed studies.

Fig. 2a shows the $P(O_2)$ dependence of the total electrical conductivity $\sigma_{\text{total}}$ of NdBaInO$_4$ and Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ at 858 °C. With decreasing $P(O_2)$, the $\sigma_{\text{total}}$ decreased in the high $P(O_2)$ range (region [A] and [B] in Fig. 2a), was constant in the intermediate $P(O_2)$ range (region [C] in Fig. 2a) and increased in the low $P(O_2)$ range (region [D] in Fig. 2a). The slope of $\log(\sigma_{\text{total}})$ versus $\log(P(O_2))$ of NdBaInO$_4$ in the $P(O_2)$ range from $5.9 \times 10^{-4}$ to $2.0 \times 10^{-1}$ atm is $0.215(2)$ and of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ in the $P(O_2)$ range from $5.7 \times 10^{-3}$ to $2.0 \times 10^{-1}$ atm is $0.216(6)$, which indicates that these materials show p-type conductivity in region [A], and mixed oxide-ion and hole conduction in region [B]. The constant conductivities independent of $P(O_2)$ in region [C] indicate that both NdBaInO$_4$ and Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ materials show pure oxide-ion conduction.

Fig. 2b shows Arrhenius plots of the total electrical conductivity $\sigma_{\text{total}}$ (circles in Fig. 2b) and oxide-ion conductivity $\sigma_{\text{ion}}$ (triangles in Fig. 2b) of NdBaInO$_4$ (black) and Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ (red). Over the entire temperature range, the total electrical conductivity $\sigma_{\text{total}}$ and oxide-ion conductivity $\sigma_{\text{ion}}$ of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ are higher than those of NdBaInO$_4$. For example, the $\sigma_{\text{total}}$ and $\sigma_{\text{ion}}$ of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ at 858 °C were $7.3 \times 10^{-4}$ S cm$^{-1}$ and $7.7 \times 10^{-4}$ S cm$^{-1}$, respectively, higher than those of NdBaInO$_4$ 1.0 $\times 10^{-3}$ S cm$^{-1}$ and $3.6 \times 10^{-3}$ S cm$^{-1}$, respectively. The hole conductivities of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ and NdBaInO$_4$ were calculated to be $6.5 \times 10^{-3}$ and $9.6 \times 10^{-4}$ S cm$^{-1}$, respectively, at 858 °C. The activation energies of total, oxide-ion, and hole conductivities of Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ were $0.685(7)$, $0.795(10)$, and $0.673$ eV, which are lower than those of NdBaInO$_4$ ($0.952(13)$, $0.91(4)$, and $0.953$ eV). Therefore, 10 mol% Sr doping into NdBaInO$_4$ improves the oxide-ion conductivity and lowers its activation energy.

To investigate the structure changes in NdBaInO$_4$ by 10 mol% Sr doping, Rietveld analysis was conducted for Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ based on the synchrotron XRPD and NPD data using RIETAN-FP and Z-Code. Nd$_{0.8}$Sr$_{0.1}$BaInO$_{3.95}$ is isostructural with NdBaInO$_4$ (space group $P2_1/c$) and has seven
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dependent sites at the general position, Nd, Ba, In, O1, O2, O3, and O4 (Table 2).* The site preference of Sr was investigated in a preliminary analysis that gave the best reliable factors, \( R_{wp} \) and \( R_{un} \), in the case that Sr exists at the Nd site (Table S2 in the ESI†). Here, \( R_{wp} \) is the weighted reliability factor of profile intensity and \( R_{un} \) is the reliability factor based on integrated intensities. Therefore, the occupancy factors were fixed to \( g(\text{Nd,Nd}) = 0.9 \) and \( g(\text{Sr,Nd}) = 0.1 \) in the final refinement. Here, \( g(Y,X) \) represents the occupancy factor of atom Y at the X site. The refinement of the occupancy factors of the oxygen atoms using common values for all oxygen atoms yields 0.9842(10), which clearly indicates the existence of oxygen vacancies. The value agrees with the expected value of 0.9875 calculated from the charge balance. In the final refinement, the occupancy factors of oxygen atoms were fixed to 0.9875. The TGA of Nd_{0.9}Sr_{0.1}BaInO_{3.95} showed 0.18% weight loss between 50 and 800 °C, which corresponds to \( \delta = 0.05 \) of Nd_{0.8}Sr_{0.2}BaInO_{3.95–\delta} (Fig. 3). Here, \( 0.05 + \delta \) is the amount of oxygen vacancies. Thus, the occupancy factors of oxygen atoms were fixed to 0.975 for the high-temperature (800 °C) data. The final Rietveld patterns are shown in Fig. 4a and b. The final refined atomic coordinates are shown in Table 1 for the TOF neutrons data and Table S1 in the ESI† for the synchrotron X-ray and the angle dispersive type neutron data.

Comparing the unit-cell parameters between 24 °C and 800 °C, the \( a, b \)- and \( c \)-axes increased and the \( \beta \)-angle decreased with increasing temperature. The average thermal expansion coefficients between 24 °C and 800 °C were found to be \( \alpha_a = 1.23(4) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_b = 1.07(3) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_c = 0.72(4) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_\beta = -3.73(17) \times 10^{-5} \text{ K}^{-1} \), and \( \bar{\alpha} = 1.06(2) \times 10^{-5} \text{ K}^{-1} \) (the definition of these coefficients are described in section D of the ESI†). These average thermal expansion coefficients of Nd_{0.9}Sr_{0.1}BaInO_{3.95} are similar to those of NdBalInO_{4} between 20 °C and 1000 °C (\( \alpha_a = 1.42(2) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_b = 1.176(14) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_c = 0.77(3) \times 10^{-5} \text{ K}^{-1} \), \( \alpha_\beta = -3.81(4) \times 10^{-5} \text{ K}^{-1} \),

![Fig. 2](image)

(a) Partial oxygen pressure \( p(O_2) \) dependence of the total electrical conductivity \( \sigma_{total} \) (858 °C) of NdBalInO_{4} (black) and Nd_{0.9}Sr_{0.1}BaInO_{3.95} (red). The dominant carriers are electron holes in \( p(O_2) \) region [A], oxide ions and electron holes in [B], oxide ions in [C], and the oxide ions and electrons in [D]. (b) Arrhenius plots of the total conductivity \( \sigma_{total} \), oxide ions and electron holes in [B], oxide ions in [C], and the oxide conductivity.

### Table 1 Crystallographic data of Nd_{0.9}Sr_{0.1}BaInO_{3.95–\delta}. Comparison with NdBalInO_{4}

| Source and facility | TOF Neutron iMATERIA, J-PARC | Synchrotron BL19B2, SPring-8 | Neutron HRPD, HANARO | Ref. 8 |
|-------------------|-----------------------------|-----------------------------|----------------------|-------|
| Chemical formula  | Nd_{0.9}Sr_{0.1}BaInO_{3.95} | Nd_{0.9}Sr_{0.1}BaInO_{3.95} | Nd_{0.9}Sr_{0.1}BaInO_{3.95} | NdBalInO_{4,00} |
| Formula weight    | 453.92                      | 453.92                      | 453.20               | 460.39 |
| Temperature / °C  | 24                           | 27                          | 800                  | 20    |
| Wavelength / Å     | Time of flight \( (d = 0.494 - 5.223 \text{ Å}) \) | 0.399662(2) | 1.83432(4) |
| Crystal system     | Monoclinic                   | Monoclinic                   | Monoclinic           | Monoclinic |
| Space group        | \( P_2_1/c \)                | \( P_2_1/c \)                | \( P_2_1/c \)        | \( P_2_1/c \) |
| \( a / \text{Å} \)  | 9.106468(17)                 | 9.10285(12)                 | 9.2060(17)           | 9.09538(3) |
| \( b / \text{Å} \)  | 6.050490(11)                 | 6.04769(5)                  | 6.0999(11)           | 6.04934(2) |
| \( c / \text{Å} \)  | 8.268786(19)                 | 8.26670(9)                  | 8.2984(17)           | 8.25620(2) |
| \( \beta / \text{Å} \)| 103.40613(14)                | 103.3924(9)                 | 103.057(12)          | 103.4041(3) |
| Unit-cell volume / Å\(^3\) | 443.184(2)                  | 442.716(8)                  | 453.95(15)           | 441.89(2) |
| \( Z \)            | 4                           | 4                           | 4                    | 4     |
| Calculated density / Mg m\(^{-3}\) | 6.81                       | 6.81                       | 6.64                | 6.92  |
| \( R_{wp} \)       | 0.0458                      | 0.0230                      | 0.0362               |       |
| \( R_p \)          | 0.0334                      | 0.0150                      | 0.0280               |       |
| Goodness of fit    | 2.994                       | 1.000                       | 1.860                |       |
| \( R_{ah} \)       | 0.0534                      | 0.0139                      | 0.0297               |       |
| \( R_f \)          | 0.0295                      | 0.0117                      | 0.0156               |       |

*TOF: Time-Of-Flight.
and $\alpha = 1.176(15) \times 10^{-5}$ K$^{-1}$. There was an anisotropy observed in the thermal expansion. The average thermal expansion coefficients are similar for the $a$- and $b$-axes, whereas that of the $c$-axis is lower than the others. The average linear thermal expansion coefficients $\alpha$ of Nd$_{0.6}$Sr$_{0.4}$BaInO$_3$ (1.06(2) $\times 10^{-5}$ K$^{-1}$) and NdBaInO$_3$ (1.176(15) $\times 10^{-5}$ K$^{-1}$) are close to that of yttria stabilized zirconia (YSZ), which is favourable for using this material as a cathode in SOFC applications. The average thermal expansion coefficients of 3 and 8 mol% Y$_2$O$_3$-ZrO$_2$ between 20 and 1000 °C were reported to be $1.08 \times 10^{-5}$ and $1.05 \times 10^{-5}$ K$^{-1}$, respectively.$^{14} $

The crystal structure of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ at 24 °C comprises the A rare earth structure $A_2O_3$ ([Nd,Sr]$_{2/8}$Ba$_{6/8}$InO$_3$) and the perovskite (A$^+$A$^0$)BO$_3$ ([Nd,Sr]$_{2/8}$Ba$_{6/8}$InO$_3$) units (Fig. 4c) which belongs to the same structural family as NdBaInO$_3$.$^4$ Here, A and A$^+$ are relatively large cations and B is a smaller cation. The unit-cell volume at 24 °C of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ (443.184(2) Å$^3$) is slightly larger than that of NdBaInO$_3$ (441.8905(3) Å$^3$). The larger volume is ascribed to the larger ionic radius of Sr$^{2+}$ (1.21 Å) for coordination number (CN) of 7) than that of Nd$^{3+}$ (1.046 Å for CN = 7). The calculated bond valence sums (BVSs)$^{38}$ from the bond lengths are 1.77 for Ba, 2.85 for (Nd$_{0.8}$Sr$_{0.2}$) and 2.99 for In sites in Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$. These values are consistent with their formal charges 2, 2.9, and 3, respectively, which indicates the validity of the refined crystal structure of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$.

As described above, Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ contains oxygen vacancies, while there are no significant oxygen vacancies within the 3σ of refined occupancy in NdBaInO$_4$ at room temperature, where $\sigma$ is the estimated standard deviation.$^4$ Considering that Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ has a much higher oxide-ion conductivity than NdBaInO$_4$, the dominant carrier for the oxide-ion conduction in Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ is the oxygen vacancy. The activation energy of the oxide-ion conduction is a little lower for Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ (0.795(10) eV) than that for NdBaInO$_4$ (0.91(4) eV). The lower activation energy of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ is attributable to the larger bottleneck size for the oxide-ion diffusion in Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ compared with NdBaInO$_4$. TGA of NdBaInO$_4$ and Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ showed little weight loss (around 0.02%) above 600 °C. Therefore, the effect of the carrier concentrations on the activation energy is thought to be negligible.

Diffusion pathways of oxide ions in the crystal structure of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ and NdBaInO$_4$ were investigated by the bond valence based energy (BVE)$^{27}$ using the program.

### Table 2
Occupancy factors, atomic coordinates and atomic displacement parameters of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ obtained from the time-of-flight neutron powder diffraction data (MATERIA, J-PARC) measured at 24 °C

| Site label | Atom | $Y$ | $g(Y,X)^{a}$ | $x$ | $y$ | $z$ | $U^{b}$ (Å$^2$) |
|-----------|------|-----|-------------|-----|-----|-----|----------------|
| Nd        | Nd   | 0.9 | 0.45269(5)  | 0.74731(11) | 0.10734(6) | 0.00819 (U$_{eq}$) |
| Sr        | 0.1  |     |             |       |       |     |                |
| Ba        | Ba   | 1   | 0.14825(7)  | 0.25034(18) | 0.0328(11) | 0.00933 (U$_{eq}$) |
| In        | In   | 1   | 0.83211(9)  | 0.2542(2)  | 0.26064(14) | 0.003(19)         |
| O1        | O    | 0.9875 | 0.18155(8) | 0.80283(9) | 0.04782(12) | 0.01422 (U$_{eq}$) |
| O2        | O    | 0.9875 | 0.89669(11) | 0.98872(17) | 0.26951(12) | 0.00988 (U$_{eq}$) |
| O3        | O    | 0.9875 | 0.38341(9)  | 0.5429(13)  | 0.32909(11) | 0.01730 (U$_{eq}$) |
| O4        | O    | 0.9875 | 0.65046(8)  | 0.50812(15) | 0.12937(11) | 0.01549 (U$_{eq}$) |

Note: $g(Y,X)^{a}$: occupancy factor of atom $X$ at the $Y$ site. $U^{b}$: Atomic displacement parameter. $U^{eq}$: Equivalent isotropic atomic displacement parameter.

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**Fig. 3** TGA curve of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$ measured in Ar. This figure shows the second cycle (first and third cycles are shown in the ESI). The green dash lines indicate the $\delta$ of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$. The weight loss from 50 to 800 °C was 0.18 wt%, which corresponds to the increase in the oxygen vacancy content $\delta = +0.05$. 

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**Fig. 4** A) Crystallographic unit cell of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$. B) Bond lengths and bond valences of Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$. C) Bond valence based energy (BVE) for Nd$_{0.9}$Sr$_{0.1}$BaInO$_{3.95}$.
Conclusions

The oxide-ion conductivity has been increased and the activation energy of oxide-ion conduction has been lowered by the substitution of Nd with Sr cations in NdBalO4. Nd0.9Sr0.1BalO3.95 showed the highest electrical conductivity among Nd1−xSrxBalO4−x/2 (x = 0, 0.1, 0.2 and 0.3). The oxide-ion conductivity $\sigma_{\text{ion}}$ of Nd0.9Sr0.1BalO3.95 was $7.7 \times 10^{-4}$ S cm$^{-1}$ at 858 °C, which is higher than that of NdBalO4 ($\sigma_{\text{ion}} = 3.6 \times 10^{-4}$ S cm$^{-1}$ at 858 °C). The crystal structure of Nd0.9Sr0.1BalO3.95 has been analysed, and we have confirmed that Sr exists at the Nd site. Nd0.9Sr0.1BalO3.95 contains oxygen vacancies, which were not observed for NdBalO4 at room temperature. Thus, the increase of the oxide-ion conductivity is mainly attributed to the increase of the carrier concentration. BVE calculations indicated two-dimensional oxide-ion diffusion in the $A_2O_3$ unit on the $bc$-plane and a decrease of the energy barrier by the substitution of Nd with Sr cations.

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