Synthesis and characterisation of \( \text{Sr}_4\text{Fe}_{3-x}\text{Cr}_x\text{O}_{10-\delta} \): Stabilisation of \( n=3 \) Ruddlesden-Popper phases through \( \text{Cr} \) doping

A. Jarvis\(^a\), F.J. Berry\(^a\), J.F. Marco\(^b\), M. Sanchez-Arenillas\(^b\), G. Cibin\(^c\), O. Clemens\(^d\),\(^e\), P.R. Slater\(^a\),\(^**\)

\(^a\) School of Chemistry, University of Birmingham, Birmingham, B15 2TT, UK
\(^b\) Instituto de Química Física “Rocasolano”, CSIC, Serrano 119, Madrid, 28006, Spain
\(^c\) Diamond Light Source, Limited, Didcot, OX11 0DE, Oxfordshire, UK
\(^d\) Materials Design by Synthesis, Technical University Darmstadt, Alarich-Weiss-Str. 2, 64287, Darmstadt, Germany
\(^e\) Karlsruhe Institute of Technology, Institute of Nanotechnology, Hermann-von-Helmholtz Platz 1, 76344, Eggenstein-Leopoldshafen, Germany

** Corresponding author.
* Corresponding author.

E-mail address: p.r.slater@bham.ac.uk (P.R. Slater).

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1. Introduction

Ruddlesden-Popper type compounds have the general formula \( \text{An}_1\text{M}_n\text{O}_{3n+1-x} \) (typically \( A \) is a rare earth, alkaline earth, \( M \) is a transition metal), and are constructed of perovskite-type layers separated by rock salt type blocks. While \( n = 1 \), 2 phases are typically straightforward to prepare, the synthesis of higher order \( (n > 2) \) systems is difficult. In this paper we show that chromate \( (\text{CrO}_4^{2-}) \) doping can be exploited to stabilise new \( n = 3 \) Ruddlesden-Popper systems, \( \text{Sr}_4\text{Fe}_{3-x}\text{Cr}_x\text{O}_{10-\delta} \), without chromate doping, a mixture of the \( n = 2 \) phase \( \text{Sr}_3\text{Fe}_{2-x}\text{O}_{7-\delta} \) and perovskite-type \( \text{SrFeO}_{3-\delta} \) is obtained. This can be explained by the stabilisation of the central perovskite building block by chromate incorporation, similar to prior work on sulfate and carbonate doping in this system. The structure, and \( \text{Fe}/\text{Cr} \) oxidation states were evaluated by X-ray diffraction, \( ^{57}\text{Fe} \) Mössbauer spectroscopy and X-ray absorption spectroscopy supporting the incorporation of \( \text{Cr} \) as \( \text{CrO}_4^{2-} \). In order to examine the potential of these new systems for use as a SOFC cathode material, conductivity studies were carried out, which showed semiconducting behaviour with slightly higher conductivities than the sulfate doped counterparts.

\( \text{La}_3\text{Ni}_2\text{O}_{7-\delta} \) and \( \text{La}_4\text{Ni}_3\text{O}_{10-\delta} \) have been prepared and shown to display improved thermal stability, electrical conductivity and electrode performance compared to \( \text{La}_3\text{NiO}_{4-\delta} \) [5]. A key challenge for higher order \( (n > 2) \) Ruddlesden-Popper phases is their synthesis. Thus, for example, both \( \text{La}_3\text{Ni}_2\text{O}_{7-\delta} \) and \( \text{La}_4\text{Ni}_3\text{O}_{10-\delta} \) will decompose at elevated temperatures (typically above 1100 °C) as oxygen loss leads to increased levels of oxide ion vacancies and hence instability in the structure. Similarly, while the \( n = 2 \) Ruddlesden-Popper phase, \( \text{Sr}_3\text{Fe}_{2-x}\text{O}_{7-\delta} \), is straightforward to synthesise, attempts to prepare the \( n = 3 \) phase, \( \text{Sr}_4\text{Fe}_{3-x}\text{O}_{10-\delta} \), in air produce a mixture of \( \text{SrFeO}_{3-\delta} \) and perovskite-type \( \text{SrFeO}_{3-\delta} \). This can be related to instabilities in the middle perovskite layer due to high oxide ion vacancy concentration. In prior work, we have shown that the introduction of oxyanion groups into perovskite systems can help to enhance the stability of phases containing large amounts of oxygen vacancies, which can be attributed to their lower coordination preference (tetrahedral (sulfate [17–21], phosphate [17,21–25], silicate [26–29]); trigonal planar (borate/carbonate [19,22,30–37])) which allocates the

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ion vacancies. Thus, Si incorporation leads to oxide ion vacancies in these oxyanion dopants is that they adopt a lower coordination than 6, which would be further increased by introduction of the smaller Si\(^{4+}\) silicate doping in SrMnO\(_3\). Using Si doping of these materials as an example, it can be expected that, assuming no change in oxygen content, the hexagonal perovskite would be obtained for both undoped and doped materials. This is due to the high tolerance factor (\(t\)) for SrMnO\(_3\), which would be further increased by introduction of the smaller Si\(^{4+}\), assuming no change in oxygen content. However, the critical point with these oxyanion dopants is that they adopt a lower coordination than 6, and so their inclusion requires either the presence or the creation of oxide ion vacancies. Thus, Si incorporation leads to oxide ion vacancies in SrMnO\(_3\) (replacement of octahedral Mn\(^{6+}\) with tetrahedral SiO\(^{4-}\)). For charge balance, partial reduction of the remaining Mn\(^{3+}\) occurs to give mixed valent Mn\(^{4+}/\)Mn\(^{3+}\). The increased size of Mn\(^{2+}\) outweighs the influence of the smaller Si\(^{4+}\), leading to an overall reduction in the tolerance factor and the change to a cubic perovskite. Furthermore, the mixed valency leads to an increase in electronic conductivity. Similar effects are seen for doping in SrCoO\(_3\). Such doping approaches can be extended to Ruddlesden-Popper type compounds, with previous studies having shown sulfate [20,38] (Fig. 1), carbonate [39] and combined sulfate/carbonate [40] incorporation into Sr\(_2\)Fe\(_{10}\)O\(_{16}\), although in most cases, evacuated sealed tubes were required to allow the high temperature synthesis without loss of the oxyanion group. In these cases, the stabilisation of the \(n = 3\) Ruddlesden-Popper is attributed to the stabilisation of oxide ion vacancies around the oxyanion dopant. Given the potential of Cr to be incorporated as a CrO\(^{4-}\) group, we illustrate here that this doping strategy can be similarly utilised to stabilise the \(n = 3\) member in air, and investigate the structures and conductivities of these doped systems.

2. Experimental

The chromium doped Sr\(_2\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10}\)\(_{\delta}\) series (\(x = 0.2–0.4\)) were prepared using stoichiometric amounts of Cr\(_2\)O\(_3\), SrCO\(_3\) and Fe\(_2\)O\(_3\), which were intimately ground and heated to 950 °C for 12 h. Samples were then reground and heated to 1000 °C for 12 h, with a further regrinding and heat treatment to 1050 °C for 12 h in air. To ensure maximum oxygen content, samples were annealed at 350 °C for 12 h in air. Due to potential hazards associated with formation of Cr\(^{6+}\) during the synthesis, all syntheses were performed in a furnace in a fume cupboard.

Powder X-ray diffraction (Analytical Empyrean diffractometer equipped with a Pixel 2D detector (Cu K\(_\alpha\) radiation)) was utilised in order to determine phase purity and for subsequent structure refinement. Rietveld refinements (tetragonal space group, I\(_4/\)mmm) were carried out using the GSAS suite of programs [41] on these Cr doped Ruddlesden-Popper samples. Lattice parameters and sample displacement parameters were refined for all samples. Due to anisotropic broadening in the XRD data, uniaxial strain models were included into the refinements. For all sites atom positions were refined, with oxygen occupancies additionally refined. Thermal parameters were constrained for Sr, Fe/Cr and O sites and fixed due to high correlation with site occupancies.

\(^{57}\)Fe Mössbauer spectra were recorded at 298 K in constant acceleration mode using an approximately 25 mCi Co/Rh source. The isomer shifts were referred to the centroid of the spectrum of metallic iron at room temperature.

Cr K-edge X-ray absorption spectroscopy (XAS) spectra were collected for Sr\(_2\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10}\)\(_{\delta}\) and standard materials, LaCrO\(_3\) and SrCrO\(_4\), on beamline B18 at Diamond Light Source (Rutherford Appleton Lab, Harwell, UK). Processing of data was performed using the Athena Software package [42].
Thermogravimetric analysis (Netzch STA 449 F1 Jupiter Thermal Analyser with mass spectrometry attachment) were carried out under N2 up to 1000 °C.

Pellets for 4 probe conductivity measurements were prepared by ball milling (350 rpm for 1 h, Fritsch Pulverisette 7 planetary mill) the samples, before then pressing into pellets. Pellets were then sintered at 1050 °C for 12 h after which four Pt electrodes were attached with Pt paste (and heated to 900 °C for 1 h to ensure good contact) and finally annealed at 350 °C for 12 h in air to ensure full oxygenation.

3. Results and discussion

3.1. X-ray diffraction characterisation

The X-ray diffraction data showed that Cr doping was successful in allowing the synthesis of the n = 3, Sr₄Fe₃₊ₓCrₓO₁₀₋ₓ phase. Fig. 2 shows the XRD data for x = 0, 0.2, 0.25, 0.3, 0.35, 0.4 samples: without Cr doping (x = 0), no n = 3 phase is obtained, but rather a mixture of Sr₄Fe₂O₇ and SrFeO₃-x is obtained. On Cr doping, the successful formation of the n = 3 Ruddlesden-Popper phase, Sr₄Fe₃₋ₓCrₓO₁₀₋ₓ, is observed (Fig. 2a). The stabilisation of the n = 3 phase can be more clearly seen in the 2θ range 40–60° (Fig. 2b), where there is a clear difference in the diffraction data between the undoped and chromate doped phases. At higher Cr contents an extra impurity phase, SrCrO₄, is found in addition to the Ruddlesden-Popper type phase, indicating that the Cr solubility in the structure had been exceeded (Supplementary Information).

The structures of the resultant phases were evaluated through Rietveld refinement using the XRD data. Due to the X-ray scattering factors of chromium and iron being similar, the individual occupancy of these elements cannot be distinguished. Therefore the occupancy of all the transition metal (Fe/Cr) sites were set to 1. The refinements suggested the presence of a small amount of perovskite phase (~3–7%), Sr(Fe/Cr)O₃₋ₓ, which was added as a second phase. Further improvements to the Rietveld refinement fits were achieved by including an anisotropic broadening model [43] to the refinements, suggesting the possibility of stacking faults within the structure (an example Rietveld fit is shown in Fig. 3). The presence of small perovskite impurities and stacking faults

![Fig. 3. Observed, calculated and difference X-ray diffraction profiles for Sr₄Fe₂.75Cr₀.25O₁₀₋₀. The two phases are indicated by blue (Ruddlesden-Popper, I₄/mmm) and red ticks (perovskite Pm-3m). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image)

![Fig. 4. Variation of lattice parameters with Cr content (x) for Sr₄Fe₃₋ₓCrₓO₁₀₋ₓ, where a = ●, c = ▴ and V = ◆. Error bars not included due to errors being smaller than the size of the data markers (errors given in Table 1).](image)

<table>
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<tr>
<th>Sr₄Fe₃₋ₓCrₓO₁₀₋ₓ</th>
<th>Cr (x)</th>
<th>a (Å)</th>
<th>c (Å)</th>
<th>V (Å³)</th>
<th>O occupancy</th>
<th>Uiso Sr</th>
<th>Fe/Cr</th>
<th>O</th>
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<tr>
<td>Cr (x)</td>
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<td>3.8767(1)</td>
<td>28.2059(7)</td>
<td>423.91(2)</td>
<td>9.72</td>
<td>0.0163</td>
<td>0.0026</td>
<td>0.00405</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>3.8791(1)</td>
<td>28.2919(9)</td>
<td>425.72(3)</td>
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<td>0.0153</td>
<td>0.00241</td>
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<td>3.8802(1)</td>
<td>28.3292(10)</td>
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<td>0.0141</td>
<td>0.0017</td>
<td>0.00473</td>
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<td></td>
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<td>28.3525(10)</td>
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<td>9.72</td>
<td>0.0128</td>
<td>0.0020</td>
<td>0.00495</td>
</tr>
</tbody>
</table>

Weight percentage (%)

| Ruddlesden-Popper | 97.2 | 97.1 | 96.5 | 94.7 | 91.0 |
| Perovskite (SrFeO₃) | 2.8 | 2.9 | 3.5 | 3.8 | 6.3 |
| SrCrO₄ | – | – | – | 1.5 | 2.7 |

![Table 1](image)
are common for higher order Ruddlesden-Popper systems [44,45].

The final refined structural parameters are shown in Table 1. These data show an increase in unit cell parameters with increasing chromium content up to \(x = 0.35\) (Table 1, Fig. 4). For \(x = 0.35\) and 0.4 a small additional impurity phase, SrCrO\(_4\), was shown to also be present, supporting the conclusions from the cell parameter data, that the Cr doping limit is \(x < 0.35\).

3.2. X-ray absorption spectroscopy (XAS)

The XRD data had indicated successful incorporation of Cr into the structure, but the oxidation state and coordination number needed further clarification. In order to evaluate this chromium environment/oxidation state, XAS analysis was carried out on Sr\(_4\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10-\delta}\), and compared with data collected for LaCrO\(_3\), SrCrO\(_4\) and Cr foil standards. LaCrO\(_3\) and SrCrO\(_4\) were used as reference materials for octahedral Cr\(^{3+}\) and tetrahedral Cr\(^{6+}\) (CrO\(_4^{2-}\)/CrO\(_4^{3-}\)) respectively, since previous studies have reported the presence of either Cr\(^{3+}\) and Cr\(^{6+}\) in Cr doped Ruddlesden-Popper systems. In particular, Sousa et al. [46] reported the presence of Cr\(^{3+}\) and Cr\(^{6+}\) in the Sr\(_4\)FeCrO\(_6\) Ruddlesden-Popper system. Bréard et al. [33] reported only Cr\(^{3+}\) in the SrFeCrO\(_5\) Ruddlesden-Popper system.

The X-ray absorption near edge structure (XANES) data for Sr\(_4\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10-\delta}\) and the LaCrO\(_3\) and SrCrO\(_4\) standards are shown in Fig. 5. The SrCrO\(_4\) reference material is found to have a sharp pre edge at 5994 eV which correlates with tetrahedral chromium in the 6\(^+\) oxidation state. In comparison a weak pre edge is observed for LaCrO\(_3\) which is characteristic of Cr\(^{3+}\) in an octahedral coordination. The data for Sr\(_4\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10-\delta}\) are similar to SrCrO\(_4\), with a similar sharp pre edge at 5994 eV. Therefore the XANES data support the original proposal that Cr is incorporated as CrO\(_4^{2-}\) (tetrahedral Cr\(^{6+}\)).

3.3. \(^{57}\)Fe Mössbauer spectroscopy

In order to evaluate the Fe environment in these Ruddlesden-Popper phases, \(^{57}\)Fe Mössbauer spectra were recorded from Sr\(_4\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10-\delta}\) and Sr\(_4\)Fe\(_{2.6}\)Cr\(_{0.4}\)O\(_{10-\delta}\) (Fig. 6). The spectra were fitted considering three different contributions. Their corresponding hyperfine parameters are collected in Table 2. These isomer shifts indicate that both these materials contain Fe\(^{3+}\) and Fe\(^{5+}\) with at least some of the Fe\(^{3+}\) in lower than octahedral coordination. As reported for oxyanion doped perovskite and Ruddlesden-Popper systems [20,27], disproportionation of Fe\(^{4+}\) to Fe\(^{3+}\) and Fe\(^{5+}\) can be attributed to the substitution of smaller Cr\(^{6+}\) for Fe\(^{4+}\), with the disproportionation process allowing for the release of local...
The XANES results indicate that the oxidation state of Cr is 6 as CrO$_4$ coordination is tetrahedral, which is hence consistent with the incorporation of tetrahedral CrO$_4$ by Cr doping can be attributed both to the high oxidation state and incorporation of tetrahedral CrO$_4$ by Cr doping: Sr$_4$Fe$_{2.8}$S$_{0.2}$O$_{10-x}$ and Sr$_4$Fe$_{2.75}$Cr$_{0.25}$O$_{10-x}$ (●) are prepared similarly, and indeed also forms as an impurity phase when the reduction in average Fe oxidation state, in this temperature range. The former (Fig. 8), although overall conductivities are slightly higher conductivities are observed at elevated temperatures for the n – 3 Ruddlesden-Popper phase and perovskite-related systems, with a view to stabilising new phases, and/or modifying the properties.

3.4. Conductivity measurements

The data for all Sr$_4$Fe$_{3-x}$Cr$_x$O$_{10-x}$ samples show three linear regions (Fig. 7) between 400 – 800 °C, which can be correlated with small changes in composition, and hence Fe oxidation states on heating as indicated by TGA studies. An initial increase in conductivity is observed with increasing temperature, indicative of the expected semiconducting behaviour. Above ≈ 640–670 °C a decrease in conductivity is observed which can be correlated with loss of oxygen at higher temperature which reduces the average transition metal oxidation state, as shown in prior work for sulfate doping [20]. In addition to the loss of oxygen in the temperature range 400–800 °C, thermogravimetric analysis (TGA-MS) indicated some loss of water at ≈ 640–670 °C, suggesting a partial dehydration of these systems. Deviations to the increase in conductivity are additionally observed at the lower temperature in the range ≈ 400–460 °C, which can be correlated to an additional loss of oxygen, and hence reduction in average Fe oxidation state, in this temperature range.

When comparing the conductivities of the present chromate doped samples, Sr$_4$Fe$_3$Cr$_{0.5}$O$_{10-x}$, to prior work on sulfate doped systems [20], slightly higher conductivities are observed at elevated temperatures for the former (Fig. 8), although overall conductivities are still rather low (8.4 S cm$^{-1}$ at 642 °C for x = 0.25) compared to common SOFC electrode materials [47]. Further doping studies, e.g. with Co, Cu, are planned to attempt to increase these values.

3.5. Implications of Cr doping on the formation of Sr$_4$Fe$_3$O$_{10-x}$

Overall the results show that Cr doping in place of Fe can be utilised to allow the formation of the n = 3 Ruddlesden-Popper phase, Sr$_4$Fe$_3$O$_{10-y}$. The XANES results indicate that the oxidation state of Cr is 6+ and the coordination is tetrahedral, which is hence consistent with the incorporation of CrO$_4^2$-$$. Thus the Cr$_2$O$_3$ (Cr$^{3+}$) starting reagent has been oxidised during the synthesis to Cr$^{6+}$. This is not surprising given that SrCrO$_4$ is prepared similarly, and indeed also forms as an impurity phase when the Cr doping limit increases. The stabilisation of this n = 3 Ruddlesden Popper phase by Cr doping can be attributed both to the high oxidation state and incorporation of tetrahedral CrO$_4^2$-. Undoped Sr$_4$Fe$_3$O$_{10-y}$ would be expected to have high levels of oxide ion deficiency (y) due to the high Fe oxidation otherwise needed (for y = 0, all the Fe would be 4+). Such vacancies might be expected to concentrate in the middle perovskite layer, hence causing a structural instability here, which therefore favours phase separation to the n = 2 (Sr$_3$Fe$_2$O$_7$-y) phase and perovskite-type SrFeO$_3$ as is observed in the XRD data for this system. The incorporation of Cr as CrO$_4^2$ has two beneficial effects towards the stabilisation on the n = 3 system; firstly the high oxidation state lowers the required Fe oxidation state from the parent system; secondly the incorporation as a tetrahedral unit leads to two stable vacancy positions around each CrO$_4^2$- group (as discussed in the introduction for perovskite systems, an octahedral FeO$_6^2$- group can be considered as being replaced by a tetrahedral CrO$_4^2$- group and accompanying partial reduction of other Fe sites in the structure). Thus, it is most likely not just the high Cr oxidation state, but also its lower coordination number that is key to structural stabilisation, as is also the case for CO$_3^{2-}$, SO$_4^{2-}$, which have been previously similarly shown to stabilise this higher order Ruddlesden Popper phase. The implication then is that we should consider both oxidation state and coordination preference when performing doping strategies in solid state materials.

4. Conclusions

In this work, we have shown for the first time that Cr doping can be utilised to allow the synthesis of the n = 3 Ruddlesden-Popper system, Sr$_4$Fe$_3$O$_{10-x}$. XANES data indicate that Cr is incorporated as CrO$_4^2$- (tetrahedral Cr$^{VI}$). We believe that this is accommodated in the central perovskite layer, similar to sulfate, which helps to stabilise this central layer. In comparison to prior work on sulfate doped Sr$_4$Fe$_3$O$_{10-x}$ materials, improved conductivity is reported at higher temperatures, although further doping studies are required to try to increase the conductivities further, with a view to potential for use in SOFCs. Overall, the work illustrates the potential of doping strategies involving tetrahedral units in perovskite-related systems, with a view to stabilising new phases, and/or modifying the properties.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement


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Raw experimental data can be found at: https://doi.org/10.25500/edata.bham.00000442.
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jscc.2020.121372.

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