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(<https://stm.bookpi.org/NTPSR-V5/issue/view/681>) Use of Rare Earth Oxides as Potential Cathode for IT-SOFC

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Abstract

Intermediate temperature solid oxide fuel cell (IT-SOFC) is known for its clean power generation as it produces extremely low emission which hazards the environment. IT-SOFC efficiency crucially depends on cathode performance. Rare-earth oxides with K_2NiF_4 - structure have gained much

attention towards its use as cathode because of its many encouraging properties. This study objects at synthesis of rare earth (electron) and alkaline earth metal (hole) doped cathode materials using combustion route. Examine effect of impurity addition on structural, electrical and electrochemical performance of cathode. Optimization of dopant concentration on the basis of maximum conductivity and minimum (area specific resistance) ASR followed by estimating the effect of oxygen partial pressure on electrical and electrochemical properties of doped cathode. Experimentally, the $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\sigma}$ ($x = 0.1 - 0.4$) single phase rare earth oxide is prepared using combustion synthesis. The SEM photographs depict agglomeration of the submicron sized crystallites resulted into formation of porous electrode layer. The dc conductivity showed maximum for $x = 0.2$, coinciding with minimum activation energy. The comparative low dc conductivity with literature reports is due to high porosity as obtained from agglomerated submicron crystallites. Sr-dependent conductivity in $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\sigma}$ is explained from defect chemistry. The $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\sigma}$ cathode exhibits lowest ASR ($= 1.92 \pm 0.015 \text{ Ohm-cm}^2$) at is obtained from complex impedance measurements. Analyzing ASR in reduced partial pressure atmosphere indicated that charge transfer at electrode-electrolyte interface is the rate limiting step.

Keywords: IT-SOFC; dc-conductivity; $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\sigma}$ cathode; Symmetric cell; EIS study

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Use of Rare Earth Oxides as Potential Cathode for IT-SOFC

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ABSTRACT

Intermediate temperature solid oxide fuel cell (IT-SOFC) is known for its clean power generation as it produces extremely low emission which hazards the environment. IT-SOFC efficiency crucially depends on cathode performance. Rare-earth oxides with K_2NiF_4 – structure have gained much attention towards its use as cathode because of its many encouraging properties. This study objects at synthesis of rare earth (electron) and alkaline earth metal (hole) doped cathode materials using combustion route. Examine effect of impurity addition on structural, electrical and electrochemical performance of cathode. Optimization of dopant concentration on the basis of maximum conductivity and minimum (area specific resistance) ASR followed by estimating the effect of oxygen partial pressure on electrical and electrochemical properties of doped cathode. Experimentally, the $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1 - 0.4$) single phase rare earth oxide is prepared using combustion synthesis. The SEM photographs depict agglomeration of the submicron sized crystallites resulted into formation of porous electrode layer. The dc conductivity showed maximum for $x = 0.2$, coinciding with minimum activation energy. The comparative low dc conductivity with literature reports is due to high porosity as obtained from agglomerated submicron crystallites. Sr-dependent conductivity in $Nd_{2-x}Sr_xFeO_{4+\delta}$ is explained from defect chemistry. The $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$ cathode exhibits lowest ASR ($= 1.92 \pm 0.015 \text{ Ohm-cm}^2$) at 973 K is obtained from complex impedance measurements. Analyzing ASR in reduced partial pressure atmosphere indicated that charge transfer at electrode-electrolyte interface is the rate limiting step.

Keywords: IT-SOFC; dc-conductivity; $Nd_{2-x}Sr_xFeO_{4+\delta}$ cathode; Symmetric cell; EIS study.

1. INTRODUCTION

Solid oxide fuel cells (SOFCs) are the devices which generates power electrochemically from hydrogen rich fuel source. As it contributes less to the pollution, SOFC offers a grand promise as an alternative energy source. Reduction from its normal operating temperature ($> 1000^\circ\text{C}$) to the intermediate range ($500 - 700^\circ\text{C}$) increases its viability in many ways. Selection of materials is the most crucial part in the development of this technology. Mixed-ionic electronic conductors (MIECs) are very useful in solid-state electrochemical devices like IT-SOFCs, batteries, sensors, etc. The cathode materials additionally, composed of oxide ceramic materials with high conductivity and good catalytic activity favoring the oxygen reduction reaction (ORR) [1].

In recent past, extensive studies were carried out on layered perovskite oxides with K_2NiF_4 – type structure due to their number of expedient properties [2,3]. Again, layered perovskites like K_2NiF_4 /double perovskites are compatible with CGO electrolyte i.e. shows no reaction up to a very high temperature which makes them considered for cathode material [4].

Among the mixed conducting oxides, the Ruddlesden-Popper phases $Ln_2NiO_{4+\delta}$ have been attracted greatly in last two decades [5]. The A_2BO_4 (rare earth/alkaline earth element as A – site cations and

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transition metal on the B-site) layered perovskites are deeply viewed as promising cathode adhering to their astonishing environmental stability and versatile applications. The doped alkaline earth elements has been alternative choices for cathode materials in intermediate temperature solid oxide fuel cells (IT-SOFC) because of their advanced mixed ionic and electronic conductivities [6-9]. The K_2NiF_4 -type manganates, nickelates, cuprates and ferrates are more thermally and chemically stable as compare to the corresponding perovskite -type oxides [10].

Previously, several $Ln_2NiO_{4+\delta}$ -based materials, ($Ln = La, Pr, Nd, \text{ or } Sm$) have been the wellliked choices as cathode materials for IT-SOFC [11-16]. Huang et al. in his studies on $LaSrNiO_{4+\delta}$ showed that the electrode and SDC electrolyte forms close contact with each other. He obtained the ASR of 3.90 ohmcm^2 at 973 K [17]. According to literature, increasing Sr concentration improves p-type electrical conductivity in La_2NiO_4 [17]. Over again literature says, oxygen partial pressure and preparation temperature has remarkable impact on producing dissimilar defects in K_2NiF_4 -type structure [18-21].

Similar properties are exhibited by the materials like $Ln_2FeO_{4+\delta}$ ($Ln = La, Ba$). Improved cathodic properties with Sr concentration are reported by Jin et al. [22]. They successfully obtained K_2NiF_4 -type structures for $Ba_{2-x}Sr_xFeO_{4+\delta}$ in the range $0.5 \leq x \leq 1.0$. Guo et al. prepared $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.5 - 1.0$) by glycine-nitrate method and reported lowest ASR of 2.75 ohmcm^2 at 973 K for $x = 1.0$ with $Sm_{0.2}Gd_{0.8}O_{1.9}$ (SDC) based electrolyte [23]. A comprehensive literature survey suggests that, the $Nd_{2-x}Sr_xFeO_{4+\delta}$ have been given less attention as cathode materials and there is an adequate scope still available for preparing superfine polycrystalline $Nd_{2-x}Sr_xFeO_{4+\delta}$ through alternative techniques to achieve better electrical and electrochemical properties for IT-SOFC applications.

In the light of aforesaid facts, present studies are undertaken with the aim of synthesis and investigation of $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1 - 0.4$) cathode materials using combustion technique (self-assisted/without fuel) for IT-SOFC applications. The sample is examined using various scientific techniques like X-ray powder diffraction, scanning electron microscopy, four-probe dc conductivity. Moreover, temperature and oxygen partial pressure based electrochemical impedance spectroscopic (EIS) studies were carried out supported on $Ce_{0.9}Gd_{0.1}O_{1.95}$ (GDC) electrolyte with Cathode/GDC/Cathode (symmetric cell) configuration. The details of characterizations and their analysis are discussed in sections below.

2. EXPERIMENTAL METHODS

Synthesis of materials with desired composition, structure and properties from specific application view point is a major difficulty before researchers now-a-days. Synthesis methods play an important role in the properties and performance of materials. In present study combustion synthesis method is used for material preparation. Combustion synthesis is simple and fast technique to obtain wide variety of advanced materials. Present work describes the synthesis of $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1 - 0.4$) powdered compositions as cathode material using combustion method. [16]. Briefly, Nd, Sr and Fe acetates (Sigma Aldrich, 99.9% pure) were taken as initial reagents and dehydrated at 393 K for 6 h in order to eradicate the traces of existing humidity. All of the required reagents measured in their stoichiometric fraction were dissolved in the doubly deionised distilled water. The liquid suspensions were then combined together in one beaker to homogenize and heated at 373 K using rota-mantle subjecting to constant stirring till complete water evaporation. The obtained residue was then burned in an electric muffle furnace at around 523 K. The ground powder then uniaxially compressed at 2.94 N m^{-2} pressure using Specac stainless steel die-punch and hydraulic press (UK) to obtain pellets of 9 mm diameter and 2 mm thickness. The prepared pellets were finally fired at 1273 K for 10 h. The $Nd_{2-x}Sr_xFeO_{4+\delta}$ when $x = 0.1, 0.2, 0.3$ and 0.4 are hereafter designated as NSFO-0.1, NSFO-0.2, NSFO-0.3 and NSFO-0.4, respectively.

Electrical conductivity (dc) measurements were made on sintered pellet which are previously dc sputtered on both the flat surfaces resulting in good ohmic contact using four probe dc conductivity method [14,32] in the temperature range 773 – 973 K. Before conductivity measurement, the sintered

pellets were gripped in a cell holder and heated at 973 K for 1 h so that the charge carriers should get homogenize. The resistivity measurement with temperature variation is done using four-probe dc conductivity method with the help of Keithley 6221 current source in association with 2182 A nano-voltmeter used in delta mode. The accuracy of $\pm 1^\circ\text{C}$ was managed with the help of Eurotherm 2216 e temperature controller during the entire measurements.

X-ray powder diffraction (XRPD) characterizations on the prepared samples were performed using PANalytical X'pert PRO (Philips) using $\text{CuK}\alpha$ radiations. The crystallographic measurements 2θ versus peak intensity were ranging from 10° to 100° with the step size of 0.025° and time/step of 5 s, with the help of Pixel 1D detector. The crystallite size based on Debye-Scherrer formula was calculated using software for all the compositions under study as explained elsewhere [24]. The morphological and compositional studies of the cathode on symmetric cells were done using scanning electron microscope (FEG-SEM) with EDS attachment. The sintered density of the entire samples was measured as derived from Archimedes' principle [16]. Hardness measurements were performed using the Vickers indentation technique [16,23].

The slurry/ink of optimized cathode (based on dc conductivity measurements) was prepared with 1 gram of $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ powder, PVB binder, sodium-free corn oil suspended in ethyl methyl ketone and ball milled at 100rpm for 2 h using planetary monomill (Fritsch Pulverisette-6, Germany). The 10 mol% GDC nano-powder acquired from Aldrich chemicals, pressed as described above to prepare pellets of 10 mm \times 1 mm diameter and thickness. Afterwards, the pellets were ignited at 1673 K for 6 h to obtain solid GDC pellets with sintered density of 96%. A layer of prepared slurry/ink of cathode is applied on both plain faces of GDC pellet using a spin coater to obtain symmetric cells of $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ /GDC/ $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ configuration henceforth called as Cell-0.2.

For EIS measurements, Auto-programmed Solartron 1255 B frequency response analyser along with a Solartron SI 1287 electrochemical interface is used in the frequency range from 1mHz to 1MHz, and at reduced oxygen atmosphere of 0.1% to 21% as explained elsewhere [25]. An ac signal of 50mV was applied during the measurements.

3. RESULTS AND DISCUSSION

All the results obtained from the present study are presented system wise separately in the subsequent sections.

3.1 Phase and Structural Analysis USING XRD

X-rays powder diffraction technique is used to determine the solid solubility limit and confirms/rule out the presence of various phases in the sample. It also helps to determine the crystallite size of the prepared sample. Typical X-ray powder diffraction (XRPD) spikes of $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$ ($x = 0.1, 0.2, 0.3$ and 0.4) are shown in Fig. 1(a)-(d), respectively. The diffraction pattern appears broader than typically observed for any good crystalline solids. This superfine crystalline nature of materials attributes to broadened diffracted lines. Fig. 1(a) reveals characteristics diffraction peaks (experimental) are strongly matching with tetragonal $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$ of JCPDS file No. 01-076-1876. Similar results were obtained for the compositions when $x = 0.2 - 0.4$. Non-existence of spike(s) due to primary reagent validates the formation of single-phase compounds with K_2NiF_4 structure. The reactivity of NSFO with GDC electrolyte was studied further. The XRPD pattern (not shown in this manuscript) of a cathode and GDC blend in a weight ratio of 1:1 do not show any new peaks even after heating at 1,473 K for 24 h. This ensures that, there is no chemical reaction between them which confirms brilliant chemical compatibility between $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$ cathode materials and GDC electrolyte.

A close scrutiny of Table 1 suggests that lattice cell constant a changes very minutely, the figure c , in contrast has increased appreciably with addition in Sr concentration within the solid solubility limit ($x = 0.1 - 0.4$). Parallel results are reported in literature [25,26] for nonvarying number of a , while a slow increase in c with Sr concentration for K_2NiF_4 -type materials.

Table 1. A comparison of tolerance factor (*t*), lattice cell constants (*a*, *c* and *v*), average crystallite size (*C_s*), % density (*ρ*) and micro hardness number (HV) of $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1 - 0.4$)

<i>x</i>	<i>t</i>	<i>a</i> (nm)	<i>c</i> (nm)	<i>v</i> (nm ³)	<i>C_s</i> (nm)	<i>ρ</i> (%)	<i>HV</i>
0.1	0.939	0.376 ± 0.004	1.317 ± 0.006	0.1862 ± 0.015	189.5 ± 0.045	82.81 ± 0.44	323 ± 4
0.2	0.942	0.376 ± 0.002	1.320 ± 0.005	0.1866 ± 0.018	197.9 ± 0.051	85.28 ± 0.57	350 ± 3
0.3	0.944	0.376 ± 0.007	1.322 ± 0.008	0.1869 ± 0.021	204.4 ± 0.048	87.25 ± 0.52	419 ± 6
0.4	0.945	0.376 ± 0.005	1.326 ± 0.007	0.1875 ± 0.022	206.2 ± 0.065	84.56 ± 0.48	412 ± 9

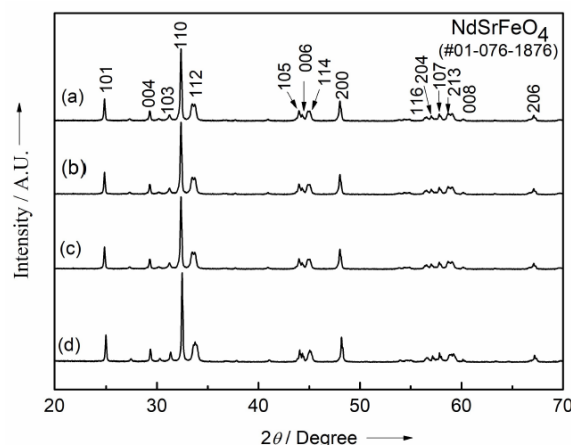


Fig. 1. X-ray powder diffraction patterns of $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$ when (a) $x = 0.1$, (b) $x = 0.2$, (c) $x = 0.3$ and (d) $x = 0.4$

A systematic variation of c and v confirms the formation of single phase solid solutions for all compositions of $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$. Moreover, table 1 illustrates nearly similar values of crystallite size (189-206 nm), sintered density (82-87%) and micro-hardness number (323419HV) for the entire series of $\text{Nd}_{2-x}\text{Sr}_x\text{FeO}_{4+\delta}$ compositions. Evidently, microstructure of solid solutions is not affected by dopant concentration. The experimental and theoretical values of at % of elements of $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ as obtained from EDS and calculations are given in Table 2. Closely matching values confirms that, the stoichiometric compounds are formed.

3.2 Morphological Study Using Sem

Scanning electron microscopy (SEM) technique is used to study morphology of the materials and to identify the particular chemical composition with the help of EDS. The SEM photographs of broken surface through the cathode-GDC interface of cell-0.2 are shown in Fig. 2. A close look at figure reveals that, there is an agglomeration in submicron crystallites of the $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ accounts for evenly distribution of grains all over the cathode (shown as an inset). Preset sintering temperature of 1273 K was chosen (with reference to our prior studies and literature reports) to obtain the best sintering performance. Figure shows, homogeneous contact throughout the interface of electrode and electrolyte is formed and no cracks or separation between them is observed despite several heating and cooling cycles of temperature. Further, the electrode forms highly porous structure is with an average thickness of $14.2\mu\text{m}$ over GDC electrolyte which appears fully dense. The estimated elemental atomic percentage for experimental and theoretical values of $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$ is compared in Table 2 supporting the formation of stoichiometric compounds.

Table 2. A comparison of experimentally and theoretically estimated at% values for elements of $\text{Nd}_{1.8}\text{Sr}_{0.2}\text{FeO}_{4+\delta}$

Element	Concentration at %	
	Theoretical	Experimental
O	57.1429	57.79 ± 0.9
Fe	14.2857	13.97 ± 0.7
Sr	02.8571	02.74 ± 0.3
Nd	25.7143	25.50 ± 0.6

3.3 Conductivity Measurements Using Four Probe Method

Electrical characterization is the backbone of any investigation on electrode materials. Therefore, the dc conductivity measurements are done on all the prepared cathode composition using four-probe method. For low resistivity measurement, magnitude of contact and spreading resistances are very

close to sample resistance. Therefore, four-point probing is used. In this method, current is sent in two probes while other two probes measure the voltage, so, measured voltage is only due to current circulated into the sample. Also, it does not include potential difference across the wire and contact. So, the measurements are accurate. In present study, the dc conductivity measurements are done on all the composition of sample under investigation and the results are discussed below. The deviation in dc conductivity for $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1, 0.2, 0.3$ and 0.4) is shown in Fig. 3 as a parametric function of temperature. Whole sample follows Arrhenius law within the entire measuring temperature range as follows,

$$\sigma T = (\sigma T)_0 \exp\left(\frac{-E_a}{kT}\right) \quad (1)$$

where $(\sigma T)_0$ is pre-exponential factor, k is Boltzmann constant, T is temperature and E_a is activation energy.

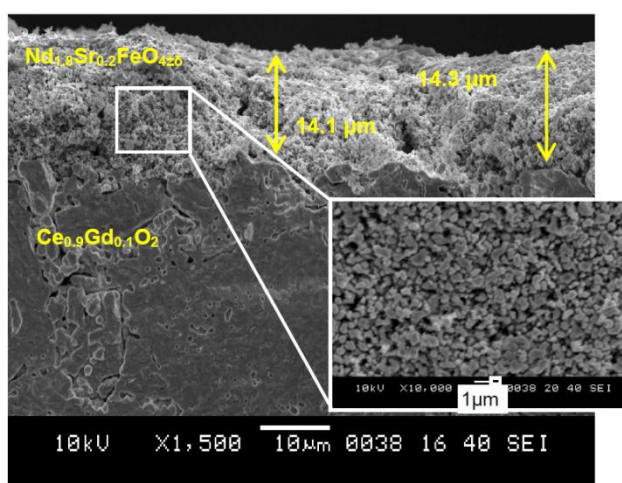


Fig.2: Scanning electron microphotograph of electrode-electrolyte interface of prepared cell (inset shows magnified image of porous cathode material)

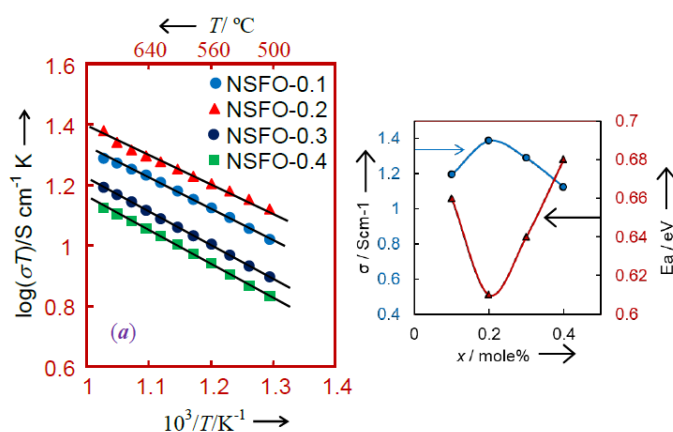


Fig. 3. (a) Arrhenius plots for $Nd_{2-x}Sr_xFeO_{4+\delta}$ when $x = 0.1 - 0.4$; (b) Variation of σ with x at 973 K

It is clear from the figure that, conductivity firstly move above with raising Sr content in $Nd_{2-x}Sr_xFeO_{4+\delta}$ but then decreases after reaching a maximum at $x = 0.2$ (Fig. 3(b)). The obtained activation energies for NSFO-0.1, NSFO-0.2, NSFO-0.3 and NSFO-0.4 are 0.66, 0.66, 0.64 and 0.68eV, respectively. It is evident from the figure that, the compositions with minimum activation

energy are in close agreement with those having maximum conductivity. An extensive study of Table 1 reveals that, crystallite size of prepared material is within the range of 189-206 nm and the sintered density is roughly similar for all the compositions. The behaviour in conductivity with respect to change in Sr content (Fig. 3(a)) is because of extrinsic defects formed as reported in literature [16,27 – 33]. Again, it is advisable to notice here that, the electrical properties in $Ln_{2-x}Sr_xMO_4$ ($M = Ni, Co, Fe, Mn$) compounds are enhanced because of the charge disproportion Fe^{3+}/Fe^{5+} according to Mössbauer spectroscopy [27]. At present, conductivity data corresponding to current system is not available in the literature to make any comparison. Since $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$ exhibited highest dc conductivity ($\sigma_{max} = 49 \text{ S cm}^{-1}$ at 913 K) compared to the other studied compositions, so, it was considered for electrochemical studies.

3.4 Electrochemical Analysis Using EIS

Electrochemical impedance spectroscopy (EIS) involving measurement of complex impedance/admittance as a function of frequency over wide range is a relatively new and powerful method of characterizing many of the electrical properties of materials and their interfaces. The value of ASR gives important information about the kinetics in the oxygen reduction reaction (ORR) on the cathode surface.

In this study, the complex impedance plots for Cell-0.2 at different temperatures are shown in Fig. 4 as a representative of all. The measurements are taken over the frequency range from 1mHz (low frequency) to 1MHz (high frequency). Figure shows depressed semi-circular arcs in the region of small frequency whereas at above frequency semi-circular arc is absent due to constraint of allocated frequency ($\leq 1\text{MHz}$). The intercept (high frequency) at real axis (R_{GDC}), belongs to GDC electrolyte and small frequency region semicircular arc is accredited to the sample electrode. The ever-increasing semicircular arcs intercepting at real axis with decrease in temperature signify an increase in resistance of GDC electrolyte (R_{GDC}) and also the ASR of electrode. The area specific resistance as a function of temperature for Cell-0.2 is shown (as an inset) in Fig. 4 for the $Nd_{2-x}Sr_xFeO_{4+\delta}$ cathodes. The Arrhenius plots are obtained taking $\log(\text{ASR})$ on the ordinate axis and $1000/T$ on the abscissa. The activation energy as determined from the slope is found to be 1.0eV for NSFO electrodes. It was seen that, initially, the ASR decreases with the addition of Sr concentration but then increases on further addition of Sr concentration. The composition $Nd_{1.8}Sr_{0.2}FeO_4$ shows lowest area specific resistance ($\approx 1.92\text{ohmcm}^2$) at 973 K in air.

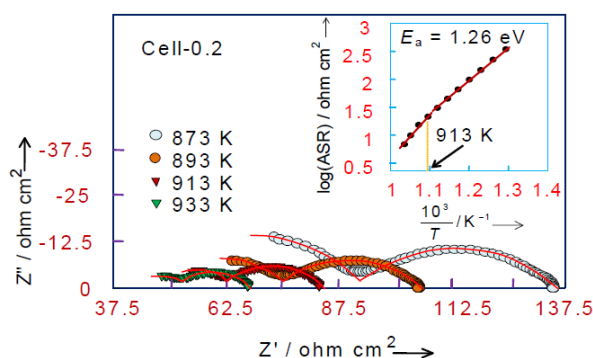


Fig. 4. Complex impedance plots for Cell-0.2 at various temperatures experimental data (symbols/points), simulated data (red line); inset shows variation of ASR

The comparison in Table 3 shows, smallest ASR value obtained in this study with those other K_2NiF_4 -typed cathode as reported in literature. Evidently, the ASR of $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$ in present study is lowest as compared to similar other reported. This lowest value of ASR is may be due to fine microstructure with moderate porosity as well as excellent matching interface between NSFO electrode and CGO electrolyte when the cell is fired at 1273 K [23]. The average size of particle was $1\mu\text{m}$, and the average thickness of the electrode over CGO electrolyte was $14.5\mu\text{m}$ (as shown in Fig.

2). Such microstructure facilitates the improved cathode properties [17,23].

The study of area specific resistance under the influence of oxygen partial pressure is useful in determining reaction rate limiting factor over the cathode surface during ORR. The variation between $\log(R_p)$ and $\log(P_{O_2})$ at 700°C is shown in the Fig. 4. Generally, variation in ASR with the reduced oxygen environment follows the below equation;

$$ASR = (ASR)_0 (P_{O_2})^{-n} \quad (2)$$

The important information about the limiting factor present in oxygen reduction reactions at cathode surface is obtained from the value of n [34,35].

$$n = 1; O_2(g) \leftrightarrow O_2(ads) \quad (3)$$

$$n = 0.5; O_2(ads) \leftrightarrow 2O(ads) \quad (4)$$

$$n = 0.25; O_{(ads)} + 2e' + V_O^{**} \leftrightarrow O_O^x \quad (5)$$

$$n = 0.1; O_{TPB}^{2-} + V_O^{**} \leftrightarrow O_O^x \quad (6)$$

The estimated value of n ($= 0.249$ at 923 K) is close to 0.25 for Cell- 0.2 (inset of Fig. 5). Fig. 5 suggests that, n value increases as the temperature is increased. Same results are obtained for Ln_2MO_4 ($M = Ni/Fe$) [17,20]. This is because, at large temperature (973 K), the transfer of ionic oxygen is improved appreciably in both the electrode and electrode-electrolyte interface. Similar reports are presented by Sun et al. for $Nd_{1.6}Sr_{0.4}NiO_{4+\delta}$ [36]. The study from P_{O_2} measurements concludes that, the charge-transfer at electrode and electrolyte interface is the rate limiting factor during oxygen reduction reaction. Various research groups have analysed and obtained similar P_{O_2} -reliant ASR nature in MIECs, based on the Eqs. 3-6 [14,37].

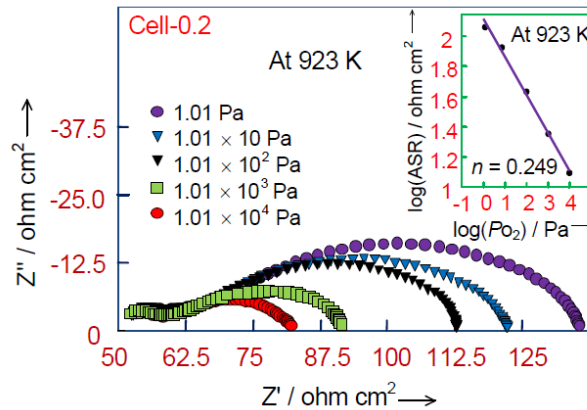


Fig. 5. Complex impedance plots of Cell-0.2 for different oxygen partial pressure; inset shows variation of ASR with oxygen partial pressure at 923 K

Table 3. A comparison of optimum ASR value obtained in this study with values reported in the literature for K_2NiF_4 -type cathode

S. N.	Cathode	ASR ($\Omega \text{ cm}^2$)	Electrolyte	T(K)	Ref.
1	$Nd_{1.8}Sr_{0.2}NiO_{4+\delta}$	0.52	GDC	973	[33]
2	$La_{1.0}Sr_{1.0}FeO_{4+\delta}$	3.90	SCO	973	[17]
3	$Ba_{1.0}Sr_{1.0}FeO_{4+\delta}$	1.42	LSGM	1073	[37]
4	$Nd_{1.0}Sr_{1.0}FeO_{4+\delta}$	2.75	SDC	973	[23]
5	$Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$	1.92	GDC	973	Present study

4. CONCLUSIONS

A number of conclusions drawn from the present study are reported here. Rare-earth oxides doped with K_2NiF_4 -type structure is successfully prepared and shows improved performance over the other perovskite type cathode materials. The series of $Nd_{2-x}Sr_xFeO_{4+\delta}$ ($x = 0.1 - 0.4$) single phase solid solutions is prepared with crystallite size in submicron range using combustion synthesis technique. XRD backs up tetragonal symmetry (I_4/mmm) of $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$. The Nd_2FeO_4 lattice increases along the c -axis with Sr content. The agglomeration of the submicron sized crystallites resulted into formation of porous electrode layer is realized from scanning electron microscopy. The dc conductivity results showed maximum for $x = 0.2$, which also exhibited minimum activation energy. The smallest dc conductivity for $x = 0.2$ is due to high porosity as obtained from agglomerated submicron crystallites. The complex impedance plots of the symmetric cell showed decrease in the real axis intercept with increased temperature in turn reduced area specific resistance (ASR). $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$ cathode exhibits lowest ASR ($= 1.92 \pm 0.0150 \text{ hcm}^2$) at 973 K. The oxygen partial pressure dependent ASR indicated charge transfer at electrode-electrolyte interface is the rate limiting factor while oxygen reduction reaction (ORR).

Based on above findings, $Nd_{1.8}Sr_{0.2}FeO_{4+\delta}$ could be viewed as a promising cathode candidate for intermediate temperature solid oxide fuel cell (IT-SOFC) applications.

FUTURE SCOPE

Microstructure of cathode material can be improved in order to increase triple phase boundaries (TPBs) to improve electrochemical activities for better performance of the cathode. All the results obtained in this study are based on the performance of symmetric cells which can be extended by preparing complete cell (button cell) and their testing can be done for its practical use.

DISCLAIMER

This present book chapter is an extended form of previously published article in "IOP Conference Series: Materials Science and Engineering, 1913 (2021) 012012."

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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WILD VEGETABLES



Editors

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Ambadi as a Wild Vegetable

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Introduction

Food is the essential source of energy required to human body. By this energy human can warm, move and work. Why do humans have to eat. The food develops and also repair the cells and tissues present in our body. It helps to carryout chemical process in our body to digest the nutrients. It also protects us against the various infection and help to recover from illness. The food is not only essential for our body health but it also essential for our mental and social health. Every food contains particular nutrition such as vitamins, carbohydrates, fats, protein, minerals, etc, which are essential for our physical and mental growth. That is single food is not enough to get all the nutrients for our body. Therefor we must have to eat various kind of food to fulfil the nutrients requirement of our body called balanced diet. For balanced and healthy diet includes the fruit, vegetables, grains, nuts etc.

Among the various food, vegetables play very important role for our body in terms of bioactive nutrients. Vegetables contains nutrients such as vitamins, minerals, fibers etc. and some non-nutrients. Eating a nutritious vegetable may reduce the risk for heart disease (including heart attack and stroke), certain types of cancers, kidney stones etc.

As per the Biodiversity International scientists total 1097 vegetable species cultivated worldwide. Out of the various species of vegetables we are familiar with less than seven percent. Most of the people deal with commercial vegetables such as potatoes, onions, tomatoes, and carrots. Vegetables can be classified in many ways depends on uses, places, edible parts etc. One of the classification of vegetables includes Flower vegetables, Leafy vegetables, Tuber vegetables, Root vegetables, Bulb vegetables, Stem vegetables, Fruit vegetables, Pod and Seed vegetables [1].

In rural areas where the market suppliers unable to provide variety of vegetables and also the cultivation of vegetables are not practiced, the local people depend on vegetables cultivated in kitchen garden and wild. The wild vegetables mostly grow in wilderness, forest, near the farmland and unused field. That is the vegetable grow without cultivation is called wild vegetables. Mostly these vegetables are available for consumption in the early days of

monsoon. Among these vegetables some are the medicinal plant. The wild vegetables contain high nutrition such as vitamins, proteins, minerals etc. Therefore, now a days some of the wild vegetables are part of our kitchen garden [2].

Indian peoples are eating the wild vegetables for many years, but due to modern lifestyle, we forget these vegetables. But still these vegetables are consumed in tribal and rural areas of India. Some of the wild vegetables are Aghada, Koat, Alu, Bhokar, Kadu kand, Ambadi, Kuda, Khurasani, Shevaga, Bhui awala, bharangi, nalli, Hastikarni, Takala, Kakad, Punarnava, ghol, Kartula, Kurdu, Fodshi, Mayalu, kala kuda, etc. [3]. This chapter is focus on study of Wild vegetable Ambadi.

To know about Ambadi

We know that green vegetables play an important role in food and nutritional security. If the green vegetables are wild then it more beneficial for human being. Ambadi is one of the green wild vegetable available all over the country. It is a queen of green vegetables. Ambadi plant is tall up to 2 to 2.5 metre with tap root system. The leaves are green, three to five lobed, long and arranged alternately on the stems. Stem is reddish purple, erect slender and cylindrical. The flowers are 8 to 10 cm in diameter, white to pale yellow with a dark red spot at the base of each petal, and have a stout fleshy calyx at the base, 1 to 2 cm wide, enlarging to 3 to 3.5 cm, fleshy and bright red as the fruit matures. Near about six months are required to mature the fruit [4,5].

The chemical constituents of Ambadi are complex carbohydrates, cellulose [3]. The leaves of Ambadi are used to prepare vegetable, pickle, chat masala while the stem of Ambadi plant is used to prepare paper. The flowers of it are used to prepare Sharbat, Jam, Jelly, Murabba while the seeds are used to prepare Besan, Chutney, Mukhwas [6]. In India Ambadi known by different names. The state wise and language wise name of Ambadi are tabulated in table 1 and the nutritional value of 100 g Ambadi are tabulated in table 2 as follows;

Table 1: state wise and language wise name of Ambadi [7]

State	Different names of Ambadi
Maharashtra	Ambadi
Assam	Nalita, Beng, Mestapat
Bengal	Patsan, Mestapat, Ambari
Gujarat	Ambari, Sheria
Karnataka	Dirin Da Rani, Kasala gida, Pindi soppu, Holada pundrike, Pundi, Pinidrikegida, Ambade, Gogu
Kerala	Kanjaru, Kanjaru
Manipur	Sougri
Odisha	Kanuriya
Tamil Nadu	Phalungu, Cetikkacuraikkirai, Pulimanjai, Valikai, Pulichhi, Palungu, Kaccurakkirai, Canampu, Pulimanji
Language	Different names of Ambadi
Marathi	Ambadi
Hindi	Pitwa, Ambadi, Ambari, Patsan, Pulu
English	Bastard jute, Brown Indian hemp Ambari hemp, Deccan hemp
Telugu	Gongura, Gogu, Gonkura, Pundikura, Gulunguchettu, Ghongukuru, Pimdikura, Gongoora, Gaynaru.
Urdu	Mushkadanah
Sanskrit	Alka, Shreyasi, Ambalika, Maryurika, Chitrapushpi, Phalamla, Keshi, Gandhapatri, Karaparni, Ambika, Vrtrtabija, Rajjudatri, Machika, Ambashtha and Sahasrvatamulika

Table 2: nutritional value of 100 g Ambadi [4]

Energy	205 kilojoule
Carbohydrates	11.31 g
Fat	0.64 g
Protein	0.96 g
Vitamins	
Vitamin A equivalent	14 µg

Thiamine (B1)	0.011 mg
Riboflavin (B2)	0.028 mg
Niacin (B3)	0.31 mg
Vitamin C	12 mg
Minerals	
Calcium	215 mg
Iron	1.48 mg
Magnesium	51 mg
Phosphorus	37 mg
Potassium	208 mg
Sodium	6 mg

Useful and Harmful effect of Ambadi

Ambadi is very useful for women's as it is good source of folic acid and iron. Again, it has Vitamin C content therefore it prevents pain during menstruation and heavy bleeding. Ambadi contained the calcium, magnesium and phosphorous these all are very much important for maintaining healthy and strong bones. If Ambadi dishes take in balanced diet then it helps to prevent bone loss and osteoporosis. In pandemic such as COVID-19 period, we must have to maintain our immunity to protect us. Ambadi contains vitamin C and ascorbic acid, both these plays a major role in boosting the immune system and increase white blood cells in the body. Homocysteine is nothing but the amino acid in the blood. If level of Homocysteine is high then there is chance to get heart and renal diseases. As we know Ambadi is good source of folate and Vitamin B6 which help to maintain the homocysteine levels low in the body. Ambadi is also good for diabetics as it contains fiber which help to control blood sugar level in the body. Fibre and magnesium content in the Ambadi provide quick relief from constipation. The property of Fibre and magnesium helps to relax the intestinal muscles, this helps to establish a smooth rhythm while passing the intestines. Again, these vitamins help attract water, which in turn softens the stool and helps it to pass easily. Ambadi is very smooth to digest and cook. It's far high in slowly digestible starch, making it an awesome vegetable to preserve and nurture the gut ecosystem. Low range in vegetarian resources ends in bad diversity inside the microbiome atmosphere within the intestine. This will accelerate getting old, lead to despair, and has pro-inflammatory

capability. Include this indigenous Ambadi on your weight-reduction plan to carry little range to your weight loss program. Tribals use Ambadi to enhance immunity, enhance gut health, and prevent diarrhoea. Its sour flavour zings up the taste buds and increases appetite [6].

As we discuss above the Ambadi are very much beneficial for us but it has some disadvantages. Ambadi contains excessive quantities of oxalic acid, overconsumption may additionally motivate oxalate poisoning that can cause unfavourable consequences by way of damaging kidneys, liver and gastrointestinal tract. Ambadi may additionally reason acidity in some people. Acidity is normally induced because of excessive utilization of pain killers, antibiotics, untimely meals, processed foods, and excessive usage of tamarind and spice inside the food. Use the blanched quantity of Ambadi for preparing dals and curries. This may relieve you from acidity related to it. It must remember that feeding mother not to consume Ambadi. People with pores and skin allergies and bronchial asthma should avoid Ambadi [6].

As per above discussion it is clear that Ambadi or we can say dishes of Ambadi has more advantages than their disadvantages for consumption. So, include the Ambadi in your balanced diet.

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