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**Structural, Optical and Electrochemical Study of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$
for Supercapacitor Applications**

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$\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ was prepared through solid state sintering route and its electrochemical performance was evaluated. The XRD pattern was consistent with an orthorhombic phase after calcination at 950 °C for 6 h, with no additional crystalline diffraction peaks detected. The SEM reveals agglomerated, rectangular-like particles with an average particle size of ~0.4 μm. The optical band gap (E_g) of the sample was calculated through the diffuse reflectance spectrum. The apparent optical gap calculated from Tauc plot is 1.7 eV representing semiconducting nature. The sample showed a high absorption in the visible light region. The highest specific capacitance at a scan rate of 5 mV/s was 95.98 F/g. Kinetic analysis indicates dominant capacitive-controlled charge storage (~71% at 10 mV s⁻¹, rising to ~88% at 100 mV s⁻¹). Linear sweep voltammetry further indicates oxygen evolution activity with an onset potential of 1.636 V and a Tafel slope of 221 mV dec⁻¹, with overpotentials of ~444 mV, 460 mV and ~470 mV at 40, 50 and 60 mA cm⁻², respectively.

Keywords: LaCuO₃; Electrochemical Properties; Supercapacitors.

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Introduction

Partially doped binary and quasi-ternary perovskites *i.e.*, $\text{La}_{1-x}\text{Sr}_x\text{CuO}_{3-\delta}$ (LSCu), $\text{La}_{1-x}\text{Sr}_x\text{MnO}_{3-\delta}$ (LSM), $\text{La}_{1-x}\text{Sr}_x\text{NiO}_{3-\delta}$ (LSN), $\text{La}_{1-x}\text{Sr}_x\text{CoO}_{3-\delta}$ (LSCo), and $\text{La}_{1-x}\text{Sr}_x\text{FeO}_{3-\delta}$ have been widely studied because of mixed ionic/electronic or electronic conductivities, which are strongly affected by chemical composition [1-3]. These characteristics make such perovskites attractive for applications including solid oxide fuel cells (SOFCs) [4], giant magnetoresistors [5], catalysts [6], and gas separation membranes [7]. Among these perovskites, $\text{La}_{1-x}\text{Sr}_x\text{CuO}_{3-\delta}$ has received significant attention for both SOFC electrode applications and high temperature superconductivity (HTS) [8, 9]. The parent stoichiometric compound LaCuO_3 was first prepared in 1972 by Demazeau *et al.* [10] and initially considered as a potential candidate for HTS; however, it was found to be metallic up to 77 K over most of its stoichiometry range [10-12]. Bringley *et al.* [11] prepared an oxygen-deficient series of $\text{LaCuO}_{3-\delta}$ ($0 \leq \delta \leq 0.5$), showing that δ can be tuned by

changing pressure and temperature, leading to structural transitions from rhombohedral to tetragonal, monoclinic, and orthorhombic phases [13]. The tetragonal and monoclinic phases are both metallic with resistivity of 100 and 300 μΩ-cm at room temperature (RT) with $\delta = 0.14$ and $\delta = 0.33$ respectively while the orthorhombic phase is an insulator at RT [11, 12, 14]. The properties of $\text{LaCuO}_{3-\delta}$ strongly depends on its oxygen non-stoichiometry. An increase in oxygen vacancies enhances reducibility by weakening the covalent bond between copper and oxygen [15] directly affecting its catalytic activity [12]. Additionally, suitable dopants can be introduced to further optimize oxygen reduction activity, as Sr doping varied TEC between 11.1 and $9.6 \times 10^{-6} \text{ K}^{-1}$ at 30 °C and 800 °C respectively, making $\text{La}_{1-x}\text{Sr}_x\text{Cu}_{2.4+\delta}$ a promising candidate for air electrode applications in solid oxide fuel cells (SOFCs) at high temperatures [16, 17]. Substituting cations at site A and B by ions of various radii and valences can create structural defects like oxygen vacancies which can play a pivotal role in improving the faradic charge process [15, 18, 19] and electrochemical performance of the materials [20-25]. Particularly,

substitution of divalent Sr^{2+} at the A-site of trivalent La^{3+} can introduce charge imbalance in the perovskite lattice, which may be compensated by oxygen-vacancy formation and/or partial oxidation of copper cations ($\text{Cu}^{2+} \rightarrow \text{Cu}^{3+}$) [26]. In the present work, the oxygen non-stoichiometry (δ) and the $\text{Cu}^{2+}/\text{Cu}^{3+}$ ratio was not experimentally quantified. Therefore, the possible coexistence of mixed Cu oxidation states and oxygen-related defects is considered here as a literature-supported mechanistic interpretation rather than as an experimentally established feature of the present sample. Such defect chemistry has been proposed in the literature as a possible contributor to reversible faradaic redox processes associated with pseudocapacitive behavior. Despite extensive study of La–Sr–Cu perovskites for catalytic, electronic, and superconducting applications, their potential as pseudocapacitive electrode materials remains largely unexplored. Therefore, in addition to examining the structural and optical properties of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$, this study also presents an in-depth investigation of its electrochemical performance, including reaction kinetics and catalytic behavior, for potential supercapacitor applications.

I. Materials and methods

$\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ was prepared through solid state sintering route, using La_2O_3 , SrCO_3 and CuO (all from Sigma Aldrich, purity > 99%). Initially the raw materials were dried to remove moisture and then weighed according to the molar ratios of the composition. The batch composition was mixed/milled using a mortar and pestle for 3 h in acetone. After mixing, powders were calcined at 950 °C for 6 h. After calcination, the powders were re-milled to dissociate the agglomerates (if any).

For the electrochemical measurement, a nickel foam working electrode was prepared. The nickel foam was cut down to the desired size of $1 \times 1 \text{ cm}^2$. After cutting, it was washed in two steps, first with deionized water and then with acetone in ultrasonic bath sonicator for 10 minutes each. This helps in removing the impurity and makes the surface uniform and suitable for the deposition of the active material ($\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$). After washing, it was kept in oven at 100 °C till drying. To deposit the active material on the nickel foam, a slurry was prepared using 80% of active material, 10% PVDF and 10% activated carbon while NMP was used as a solvent. Activated carbon was used to enhance the conductivity while PVDF

was used as a binder. After the preparation of slurry, 0.02 g of the total slurry was deposited on the nickel foam corresponding to an active material mass of 0.016 g. In the next step, the electrode was kept in oven at 100 °C for 24 h to make it completely dry and ready for use as a working electrode. In the present work, all the electrochemical parameters including specific capacitance are normalized to the mass of the active material.

The X-ray diffraction pattern of the sample was collected at room temperature using JDX-3532 (JEOL, Japan) with Cu-K α radiation ($\lambda = 0.154 \text{ nm}$). To examine the microstructure of the sample, JSM5910 (JEOL, Japan) was used. For diffuse reflectance spectroscopy of the samples, a LAMBDA 365+ (Perkin Elmer, USA) was used. The electrochemical properties of the material were measured from the data of cyclic voltammetry (CV) and linear sweep voltammetry (LSV) by testing the material in a three-electrode system using $\text{Hg}/\text{Hg}_2\text{Cl}_2$ as a reference electrode and platinum wire as a counter electrode. The sample was deposited on a nickel foam (working electrode) and submerged in the aqueous solution of 3 Molar KOH.

II. Results and Discussion

Fig. 1a shows the X-ray diffraction pattern obtained at room temperature, which is consistent with the orthorhombic reference pattern of PDF No. 41-181. No additional crystalline diffraction peaks attributable to the starting La_2O_3 or CuO phases were detected within the resolution of the present XRD measurement. The lattice parameters and unit-cell volume were obtained by least-squares fitting of the observed diffraction peak positions. The sample exhibited lattice constants of $a = 16.2708 \pm 0.0094 \text{ \AA}$, $b = 13.5087 \pm 0.0080 \text{ \AA}$, $c = 11.7985 \pm 0.0089 \text{ \AA}$ and a unit cell volume of $2593.2663 \pm 2.90 \text{ \AA}^3$, consistent with the card data. It should be noted that the PDF No. 41-181 reference card used for phase identification does not provide a space-group designation. Since the present analysis was based on reference-pattern matching and least-squares fitting of the diffraction peak positions, rather than an independent crystallographic structure refinement, a specific space group cannot be assigned reliably from the available data. Therefore, the present work identifies the crystal symmetry as orthorhombic based on the reference diffraction pattern without assigning a specific space group. The relatively large lattice parameters compared

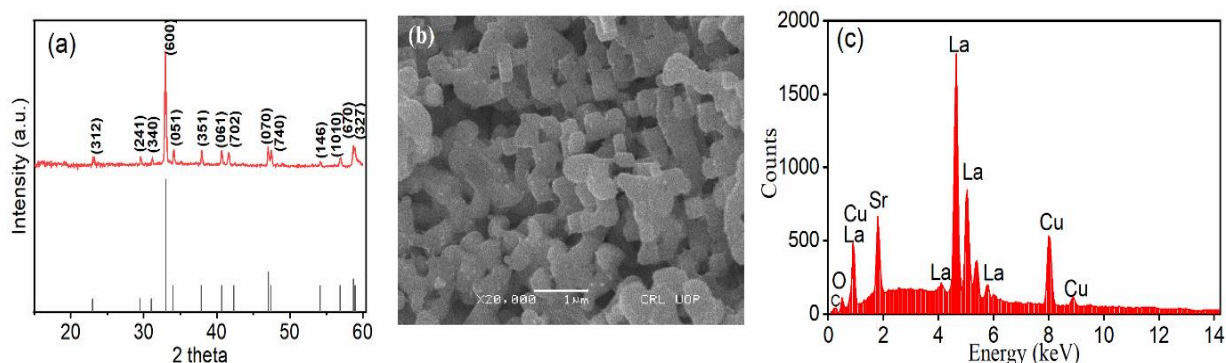


Fig. 1. (a) XRD pattern, (b) SEM micrograph and (c) EDS analysis of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$.

with the basic pseudocubic perovskite subcell indicate an expanded crystallographic cell relative to the basic perovskite unit. However, the present XRD analysis does not establish a specific superstructure model or its crystallographic origin. The SEM micrograph (Fig. 1b) of the sample shows agglomerated rectangular-like particles. The average particle size was calculated to be 0.4 μm . The corresponding EDS (Fig. 1c) spectrum for the sample confirms the presence of lanthanum, strontium, copper and oxygen elements.

The absorption spectrum of the sample (Fig. 2a) shows the high absorption in the range of 400 nm to 700 nm which lies in the visible light region. The optical band gap (E_g) for the sample is calculated through the diffuse reflectance spectrum by solving the Kubelka–Munk Eq. 1.

$$[F_R hv]^n = a(hv - E_g) \quad (1)$$

Where $F(R)$ is Kubelka–Munk function, $h\nu$ is energy of photon, a is constant of proportionality. The value of n is constant. $n = 1/2$ and $n = 2$ corresponds to direct and indirect allowed transition of electrons. Many parameters can affect the optical band gap of material such as the processing method, crystalline nature [27], average particle size [28], and unit cell parameters (lattice strain) [29]. The diffuse reflectance spectrum near the absorption edge does not exhibit a clear linear regime uniquely associated with either direct or indirect transitions. As a result, the Tauc representations for direct and indirect allowed transitions give apparent gap estimates of 1.74 eV and 1.70 eV, respectively (Fig. 2b and 2c). Therefore, the present data is insufficient to determine the absolute type of electronic transition, and it is more suitable to define the electronic behavior as an apparent optical gap of approximately 1.7 eV, confirming its semiconducting nature.

Historically, stoichiometric LaCuO_3 is metallic in nature, whereas the present $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ sample exhibits semiconducting behavior with an apparent optical gap of ~ 1.7 eV. This difference may be associated with structural distortion and possible chemical non-

stoichiometry resulting from Sr^{2+} substitution. The Sr^{2+} substitution at the La^{3+} site can alter the local charge balance and may be accompanied by changes in the Cu oxidation state and oxygen-related defects; such changes can modify the Cu–O electronic interactions and therefore influence the observed optical response. In addition, the orthorhombic structural distortion and associated changes in CuO_6 octahedral geometry may modify Cu–O–Cu bond angles and bond lengths, which can affect the electronic structure and contribute to the observed apparent optical gap. However, because the oxygen non-stoichiometry and $\text{Cu}^{2+}/\text{Cu}^{3+}$ ratio were not experimentally quantified in the present study, these effects are considered possible contributors rather than experimentally established causes [12, 30–32].

To evaluate the electrochemical performance of the sample, cyclic voltammetry (CV) and linear sweep voltammetry in the three-electrode setup were performed. The cyclic voltammogram of the sample at different scan rates in a potential window of 0–0.6 V is shown in Fig. 3a which shows a single anodic peak current on a forward scan and a single cathodic peak current on a backward scan, revealing a reversible pseudocapacitive behavior. The values of peak anodic currents (I_{pa}), cathodic currents (I_{pc}), peak anodic potential (E_{pa}), cathodic potential (E_{pc}), specific capacitance (C_p) and energy density (E_d) are listed in Table 1. The anodic and cathodic peak currents increase gradually with increasing scan rates showing linear behavior. The specific capacitance (C_p) and energy density (E_d) were calculated using Eq. 2 and Eq. 3, respectively. Where “ $\int IdV$ ” is area under the CV curve, “ m ” is mass in grams and “ $V_2 - V_1$ ” is the potential window.

$$C_p = \frac{\int IdV}{mk(V_2 - V_1)} \quad (2)$$

$$E_d = \frac{1}{2} C_p (V_2 - V_1)^2 \quad (3)$$

The specific capacitance of the sample decreases with the increase in scan rate which may be attributed to limited ion diffusion and utilization of faradic redox sites at higher current rates. The highest capacitance calculated is

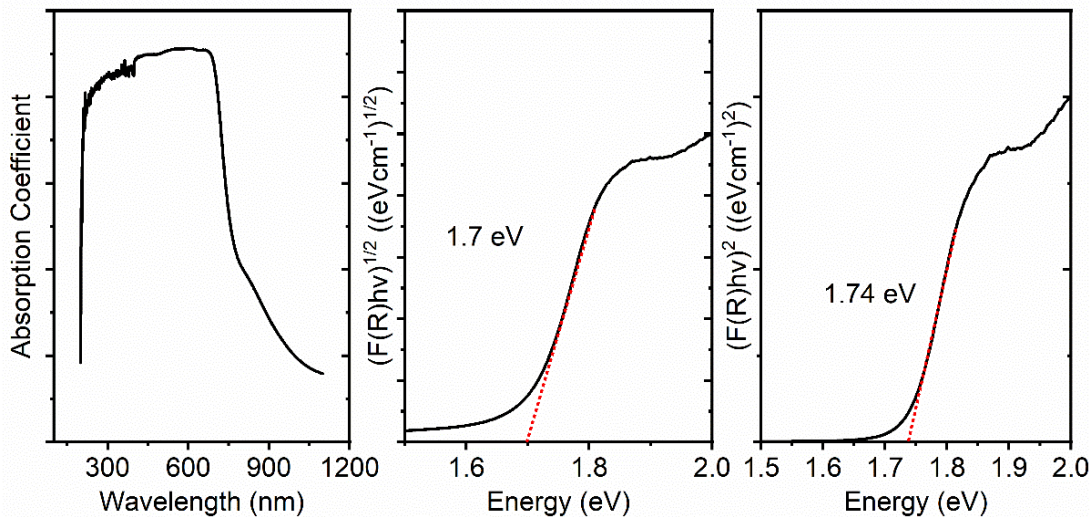


Fig. 2. (a) Absorption spectra $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ and Tauc plot for (b) direct, and (c) indirect allowed transitions.

95.98 F/g at scan rate of 5 mV/s. For deep analysis of the energy storage mechanism of LSC, Randles–Ševčík relation (I_p is proportional to $v^{1/2}$) is used to find the relationship between peak current and scan rate. Since a good linear fit is obtained from between both anodic and cathodic peak current versus square root of scan rate, it has been concluded that a fast and reversible redox reaction occurs on the interface between electrode and electrolyte (Fig. 3b). In addition, the linear relationship between log of anodic peak current density and scan rate is also considered according to general power-law relation (Eq. 4 and 5) [33, 34].

$$I = av^b \quad (4)$$

$$\log I = \log a + b \log v \quad (5)$$

Where I represent the peak current density, v represent the scan rate in mV/s, while a and b are constant. Generally, the value of b varies from 0.5 to 1. $b = 0.5$ represents the diffusion-controlled behavior, while $b = 1$ indicates that the process is capacitive-controlled [35, 36]. In this work, the value of b for anode is 0.939 which confirms the dominant capacitive and slightly diffusive contribution (Fig. 3c). For quantitative contribution of diffusion and capacitive controls process,

Dunn method is used [37], given by Eq. 6.

$$I(V) = C_1 v + C_2 v^{1/2} \quad (6)$$

$$\frac{I_{pa}}{v^{1/2}} = C_1 v^{1/2} + C_2 \quad (7)$$

Where $I(V)$ represents the current at a specific voltage and $C_1 v$ and $C_2 v^{1/2}$ corresponds to the capacitive and diffusion control contribution, respectively. The values of C_1 and C_2 are obtained from the plot (Fig. 3d). The percentage contribution of capacitive and diffusive control is also calculated as shown in Fig. 3e and Fig. 3f. At low scan rate of 10 mV/s, the capacitive contribution is 71% while the diffusion is 29% (Fig. 3e). With the increase in scan rate, the capacitive contribution increases gradually and reaches a maximum value of 88% at a scan rate of 100 mV/s (Fig. 3f). The gradual increase in the capacitive contribution may possibly be due to the limitations of ion diffusion at higher scan rates.

To evaluate the suitability of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ for potential energy-conversion applications and to examine its electrochemical response under anodic polarization, the oxygen evolution reaction (OER) was investigated. The LSV measurements were carried out without active iR-compensation and in a potential window of 1.6 V and

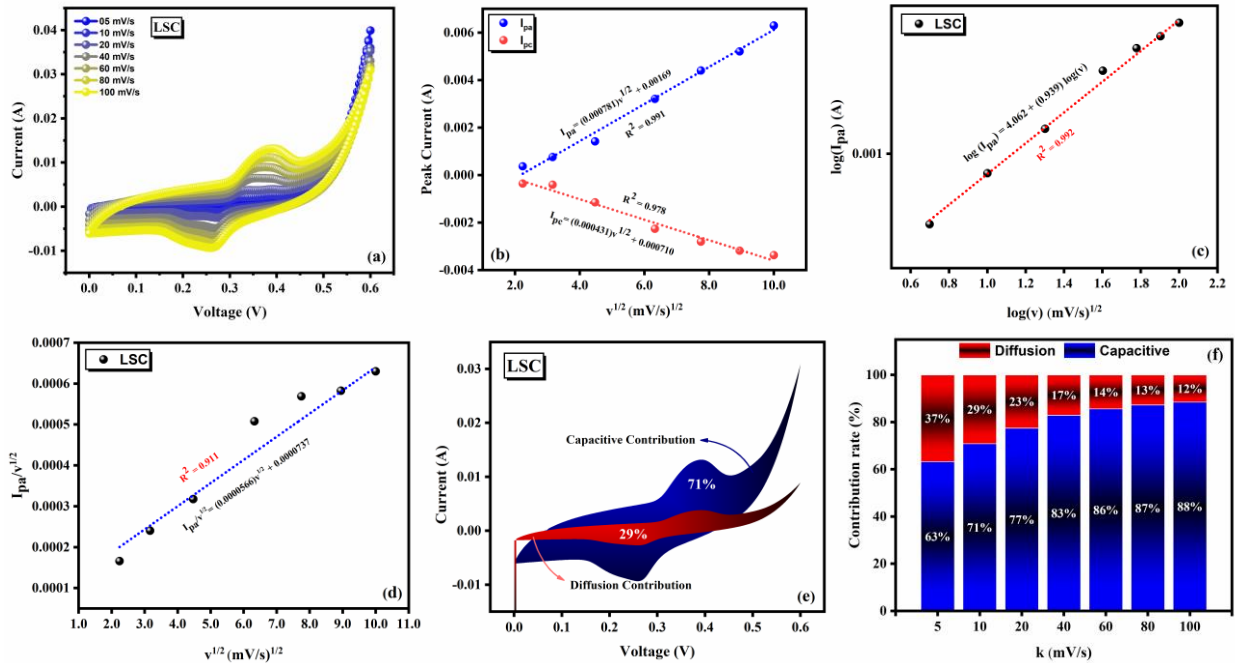


Fig. 3. (a) CV (b) peak anodic and cathodic current at different scan rates (c) linear relationship between log of peak current density of anode and log of scan rate (d) relationship between anode peak current density and square root of scan rate (e) diffusion (red) and capacitive-controlled contribution to charge storage at 10 mV/s (f) diffusion and capacitive contribution at different scan rates.

Table 1. Values of I_{pa} , I_{pc} , E_{pa} , E_{pc} , C_p , and E for $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ at different scan rates.

Scan Rate (mV/s)	5	10	20	40	60	80	100
I_{pa} (mA)	0.37	0.76	1.41	3.212	4.41	5.21	5.63
E_{pa} (V)	0.31	0.33	0.33	0.35	0.36	0.38	0.39
I_{pc} (mA)	0.35	0.40	1.14	2.26	2.80	3.18	3.37
E_{pc} (V)	0.28	0.28	0.27	0.27	0.26	0.26	0.26
C_p (F/g)	95.98	48.21	27.29	16.22	12.49	10.55	9.35
E (Wh/kg)	4.80	2.41	1.36	0.81	0.62	0.53	0.47

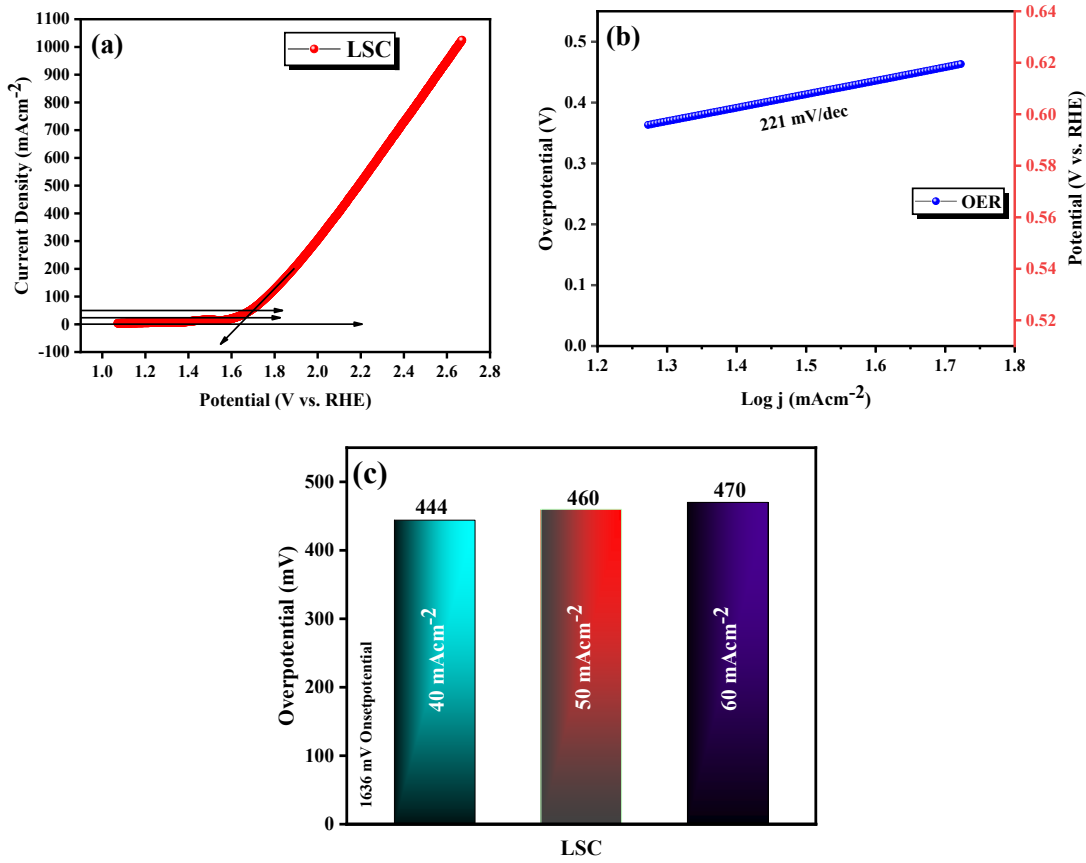


Fig. 4. (a) LSV plot (b) Tafel plot (c) kinetics of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$.

scan rate of 50 mV/s. The data was processed using Eq. 8-10. The potential conversion equation (Eq. 8) is used to convert the potential measured versus reference electrode to the Reversible Hydrogen Electrode (E_{RHE}). The Oxygen Evolution Reaction (OER) overpotential (η) was calculated by using Eq. 9 and then the Tafel slope (d) was calculated using Eq. 10 (Fig. 4b).

$$E_{\text{RHE}} = E_{\text{Hg/Hg}_2\text{Cl}_2/\text{Sat.KOH}} + 0.0598\text{pH} + 0.244 \quad (8)$$

$$\eta = E_{\text{RHE}} - 1.23 \quad (9)$$

$$\eta = c + d \log j \quad (10)$$

Here, ' j ' is the current density, and c is the Tafel constant.

The onset potential was calculated to be 1636 mV at the tangential point of LSV curve by the Tangent Extrapolation method (Fig. 4a). The apparent Tafel slope calculated from the OER was found to be 221 mV/dec. For the present $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ electrode, the semiconducting optical response and the structurally distorted perovskite framework may contribute to interfacial charge-transfer resistance during anodic polarization. In addition, gas-bubble accumulation at the electrode surface and uncompensated series resistance can become increasingly significant at the relatively high current densities used for the OER measurements. These factors may contribute to the relatively large apparent Tafel slope observed for the present electrode. However, their individual contributions were not independently

quantified in this study. The overpotential at current densities of 40 mA cm⁻², 50 mA cm⁻² and 60 mA cm⁻² is 444 mV, 460 mV and 470 mV respectively as shown in Fig. 4c. While theoretical kinetics predicts much lower values of Tafel slope, higher Tafel slopes are frequently reported specifically for transition metal oxide electrocatalysts. The reason for higher values are physical barriers and real-world bottlenecks like resistive semiconductor space-charge layers [38], tiny trapped gas bubbles on the active sites [39] and resistive oxide films that builds on the surface [40]. In several comparable systems, similar high slopes are reported in literature. For Boron-doped Diamond, reported Tafel slope ranges from 220 mV/dec up to 680 mV/dec [38, 41-44]. In a recent study, La_2NiO_4 and La_2ZnO_4 shows a slope of 220 mV/dec and 233 mV/dec, respectively [45]. $\text{SnO}_2\text{-Sb}$ also have high reported values 212-290 [46-48]. Solid-State Reaction synthesis of CoSb_2O_6 also shows Tafel slope exceeding 200 mV/dec [49]. Beside of all the physical bottlenecks, it is worth noting that no iR -compensation was applied during the measurement of these polarization curves. At high current densities, the uncompensated Ohmic drop contributes to the measured potential and may increase the apparent Tafel slope. Accordingly, the reported value of 221 mV/dec should be regarded as an apparent, uncorrected Tafel slope.

Conclusion

$\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ was prepared through a solid-state route, and the XRD pattern was consistent with an

orthorhombic phase, with no additional crystalline diffraction peaks detected. SEM analysis showed agglomerated rectangular-like particles with submicron dimensions. The optical properties of the sample revealed semiconducting behavior with an apparent optical band gap of ~ 1.7 eV and strong absorption across the visible region. The electrochemical study of the sample showed pseudocapacitive behavior with a specific capacitance of 95.98 F/g at a scan rate of 5 mV/sec. The charge storage was found to be predominantly governed by surface controlled capacitive process (at high scan rates). LSC results revealed that oxygen evolution activity, characterized by moderate onset potential and Tafel slope values comparable to other transition-metal-based oxides. The performance of the sample suggests that it can be useful for supercapacitor electrode applications, with further performance enhancement possible through material optimization.

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Data Availability Statement

Data will be made available on request.

Conflicts of Interest

The authors declare no conflicts of interest.

Khan Yaseen – MPhil student;

Naz Iqra – MPhil student;

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- [1] S.P. Simner, J.F. Bonnett, N.L. Canfield, K.D. Meinhardt, J.P. Shelton, V.L. Sprenkle, J.W. Stevenson, *Development of lanthanum ferrite SOFC cathodes*, Journal of Power Sources, 113, 1 (2003); [https://doi.org/10.1016/S0378-7753\(02\)00455-X](https://doi.org/10.1016/S0378-7753(02)00455-X).
- [2] S.C. Singhal, *Science and Technology of Solid- Oxide Fuel Cells*. MRS Bulletin 25, 16–21 (2000); <https://doi.org/10.1557/mrs2000.13>.
- [3] N.Q. Minh, *Ceramic Fuel Cells*, Journal of the American Ceramic Society, 76(3), 563 (1993); <https://doi.org/10.1111/j.1151-2916.1993.tb03645.x>.
- [4] L.J. Gauckler, D. Beckel, B.E. Buegler, E. Jud, U.P. Muecke, M. Prestat, J.L. Rupp, J.J.C. Richter, *Solid oxide fuel cells: systems and materials*, Chimia, 58(12), 837 (2004); <https://doi.org/10.2533/00094290477677047>.
- [5] N. Zhang, W. Ding, W. Zhong, D. Xing, Y.J.P.R.B. Du, *Tunnel-type giant magnetoresistance in the granular perovskite $\text{La}_{0.85}\text{Sr}_{0.15}\text{MnO}_3$* , Physical Review B, 56, 8138 (1997).
- [6] M.A. Peña, J.J.C.r. Fierro, *Chemical structures and performance of perovskite oxides*, Chem Rev, 101(7), 1981 (2001); <https://doi.org/10.1021/cr980129f>.
- [7] H.J.J.C.t. Bouwmeester, *Dense ceramic membranes for methane conversion*, Catalysis Today, 82(1-4), 141 (2003); [https://doi.org/10.1016/S0920-5861\(03\)00222-0](https://doi.org/10.1016/S0920-5861(03)00222-0).
- [8] Y.J.J.o.M.S.L. Khan, *High temperature superconductivity ($T_c \approx 50\text{K}$) in the $\text{Sr}_x\text{La}_{1-x}\text{CuO}_3$ of a new type*, Journal of Materials Science Letters, 6, 1387 (1987); <https://doi.org/10.1007/BF01689297>.
- [9] C. Michel, L. Er-Rakho, B.J.M.r.b. Raveau, *The oxygen defect perovskite $\text{BaLa}_4\text{Cu}_5\text{O}_{13.4}$, a metallic conductor*, Materials Research Bulletin, 20, 667 (1985); [https://doi.org/10.1016/0025-5408\(85\)90144-8](https://doi.org/10.1016/0025-5408(85)90144-8).
- [10] G. Demazeau, C. Parent, M. Pouchard, P. Hagenmuller, *Sur deux nouvelles phases oxygénées du cuivre trivalent: LaCuO_3 et La_2LiO , 50CuO , 50O_4* , Materials Research Bulletin, 7, 913 (1972); [https://doi.org/10.1016/0025-5408\(72\)90080-3](https://doi.org/10.1016/0025-5408(72)90080-3).
- [11] J. Bringley, B. Scott, S. La Placa, R. Boehme, T. Shaw, M. McElfresh, S. Trail, D. Cox, *Synthesis of the defect perovskite series $\text{LaCuO}_{3-\delta}$ with copper valence varying from 2+ to 3+*, Nature, 347, 263 (1990).
- [12] M. Karppinen, H. Yamauchi, T. Ito, H. Suematsu, O. Fukunaga, *High-pressure synthesis and thermal decomposition of LaCuO_3* , Materials Science and Engineering: B, 41(1), 59 (1996); [https://doi.org/10.1016/S0921-5107\(96\)01624-8](https://doi.org/10.1016/S0921-5107(96)01624-8).
- [13] A. Webb, E. Skelton, S. Qadri, E. Carpenter Jr, M. Osofsky, R. Soulen, V. Letourneau, *High temperature-high pressure synthesis of a new phase of LaCuO_3* , Physics Letters A, 137, 205 (1989); [https://doi.org/10.1016/0375-9601\(89\)90212-0](https://doi.org/10.1016/0375-9601(89)90212-0).
- [14] J. Bringley, B. Scott, S. La Placa, T. McGuire, F. Mehran, M. McElfresh, D. Cox, *Structure and properties of the $\text{LaCuO}_{3-\delta}$ perovskites*, Physical Review B, 47, 15269 (1993); <https://doi.org/10.1103/PHYSREVB.47.15269>.
- [15] R. Ao, L. Ma, Z. Guo, Q. Dai, L. Xie, J. Yang, *Positive effects of the Sr doping on LaCoO_3 perovskites for simultaneous catalytic oxidation performances of NO and Hg0*, Energy, 290, 130196 (2024); <https://doi.org/10.1016/j.energy.2023.130196>.
- [16] A. Niemczyk, Z. Du, A. Olszewska, M. Marzec, M. Gajewska, K. Świerczek, H. Zhao, B. Poudel, B. Dabrowski, *Effective oxygen reduction on A-site substituted $\text{LaCuO}_{3-\delta}$: toward air electrodes for SOFCs based on perovskite-type copper oxides*, Journal of Materials Chemistry A, 7, 27403 (2019); <https://doi.org/10.1039/C9TA09244G>.
- [17] M. Zahid, I.A. Raj, W. Fischer, F. Tietz, J.S. Alfaro, *Synthesis and investigations on the stability of $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{2.4+\delta}$ at high temperatures*, Solid state ionics, 177, 3205 (2006); <https://doi.org/10.1016/j.ssi.2006.07.041>.

- [18] M. Ahangari, E. Mahmoodi, N. Delibaş, J. Mostafaei, E. Asghari, A. Niaei, *Application of SrFeO₃ perovskite as electrode material for supercapacitor and investigation of Co-doping effect on the B-site*, Turkish journal of chemistry, 46, 1723 (2022); <https://doi.org/10.55730/1300-0527.3475>.
- [19] J. Qu, X. Guo, Z. Tian, H. Wang, X. Ye, L. Wang, S. Dong, *Effect of Sr Doping at the A Site on the Electrochemical Properties of LaCoO₃ Used for Supercapacitor Applications*, Journal of Electronic Materials, 54, 3851 (2025); <https://doi.org/10.1007/s11664-025-11872-0>.
- [20] G. George, S.L. Jackson, C.Q. Luo, D. Fang, D. Luo, D. Hu, J. Wen, Z. Luo, *Effect of doping on the performance of high-crystalline SrMnO₃ perovskite nanofibers as a supercapacitor electrode*, Ceramics International, 44, 21982 (2018); <https://doi.org/10.1016/j.ceramint.2018.08.313>.
- [21] Y. Cao, J. Liang, X. Li, L. Yue, Q. Liu, S. Lu, A.M. Asiri, J. Hu, Y. Luo, X. Sun, *Recent advances in perovskite oxides as electrode materials for supercapacitors*, Chemical Communications, 57, 2343 (2021); <https://doi.org/10.1039/D0CC07970G>.
- [22] Y. Jing, W. Li, D. Wang, X. Chang, M. He, Z. Ren, *B-site regulated bimetallic perovskite fluoride NaCo_{1-x}Ni_xF₃/reduced graphene oxide as the enhanced performance electrode material for supercapacitors*, Journal of Alloys and Compounds, 905, 164188 (2022).
- [23] Y. Liu, J. Dinh, M.O. Tade, Z. Shao, *Design of perovskite oxides as anion-intercalation-type electrodes for supercapacitors: cation leaching effect*, ACS applied materials & interfaces, 8(36), 23774 (2016); <https://doi.org/10.1021/acsami.6b08634>.
- [24] H. Mo, H. Nan, X. Lang, S. Liu, L. Qiao, X. Hu, H. Tian, *Influence of calcium doping on performance of LaMnO₃ supercapacitors*, Ceramics International, 44, 9733 (2018); <https://doi.org/10.1016/j.ceramint.2018.02.205>.
- [25] H.-s. Nan, X.-y. Hu, H.-w. Tian, *Recent advances in perovskite oxides for anion-intercalation supercapacitor: a review*, Materials Science in Semiconductor Processing, 94, 35 (2019); <https://doi.org/10.1016/j.mssp.2019.01.033>.
- [26] H.-C. Yu, K.-Z. Fung, *Role of Sr addition on the structure stability and electrical conductivity of Sr-doped lanthanum copper oxide perovskites*, Journal of materials research, 19, 943(2004); <https://doi.org/10.1557/jmr.2004.0122>.
- [27] R. Dangi, B. Basnet, M. Pandey, S. Bhusal, B. Budhathoki, K. Parajuli, S.K. Tiwari, B.P. Kafle, *Effect of oxygen vacancy on the crystallinity and optical band gap in tin oxide thin film*, Energies, 16(6), 2653 (2023); <https://doi.org/10.3390/en16062653>.
- [28] M. Sahana, C. Sudakar, A. Dixit, J. Thakur, R. Naik, V. Naik, *Quantum confinement effects and band gap engineering of SnO₂ nanocrystals in a MgO matrix*, Acta materialia, 60, 1072 (2012); <https://doi.org/10.1016/j.actamat.2011.11.012>.
- [29] L. Yang, X. Cui, J. Zhang, K. Wang, M. Shen, S. Zeng, S.A. Dayeh, L. Feng, B. Xiang, *Lattice strain effects on the optical properties of MoS₂ nanosheets*, Scientific reports, 4, 5649 (2014); <https://doi.org/10.1038/srep05649>.
- [30] J. Bringley, B. Scott, S. La Placa, T. McGuire, F. Mehran, M. McElfresh, D. Cox, *Structure and properties of the LaCuO 3-δ perovskites*, Physical Review B, 47, 15269 (1993); <https://doi.org/10.1103/PhysRevB.47.15269>.
- [31] Q. Li, Y.-X. Deng, Y.-A. Zhu, Y. Li, Z.-J. Sui, D. Chen, W.-K. Yuan, *Structural stability of Lanthanum-based oxygen-deficient perovskites in redox catalysis: A density functional theory study*, Catalysis Today, 347, 142 (2020); <https://doi.org/10.1016/j.cattod.2018.04.070>.
- [32] J.W. Furness, Y. Zhang, C. Lane, I.G. Buda, B. Barbiellini, R.S. Markiewicz, A. Bansil, J. Sun, *An accurate first-principles treatment of doping-dependent electronic structure of high-temperature cuprate superconductors*, Communications Physics, 1, 11 (2018); <https://doi.org/10.1038/s42005-018-0009-4>.
- [33] M.S. Javed, H. Lei, J. Li, Z. Wang, W. Mai, *Construction of highly dispersed mesoporous bimetallic-sulfide nanoparticles locked in N-doped graphitic carbon nanosheets for high energy density hybrid flexible pseudocapacitors*, Journal of materials chemistry A, 7, 17435 (2019); <https://doi.org/10.1039/C9TA05180E>.
- [34] V. Augustyn, J. Come, M.A. Lowe, J.W. Kim, P.-L. Taberna, S.H. Tolbert, H.D. Abruña, P. Simon, B. Dunn, *High-rate electrochemical energy storage through Li⁺ intercalation pseudocapacitance*, Nature materials, 12, 518(2013); <https://doi.org/10.1038/nmat3601>.
- [35] P. Simon, Y. Gogotsi, B. Dunn, *Where do batteries end and supercapacitors begin?* Science, 343, 1210 (2014); <https://doi.org/10.1126/science.1249625>.
- [36] Q. Wang, H. Yang, T. Meng, J. Yang, B. Huang, F.L. Gu, S. Zhang, C. Meng, Y. Tong, *Boosting electron transfer with heterointerface effect for high-performance lithium-ion storage*, Energy Storage Materials, 36, 365 (2021); <https://doi.org/10.1016/j.ensm.2021.01.003>.
- [37] J. Wang, J. Polleux, J. Lim, B. Dunn, *Pseudocapacitive contributions to electrochemical energy storage in TiO₂ (anatase) nanoparticles*, The Journal of Physical Chemistry C, 111, 14925(2007); <https://doi.org/10.1021/jp074464w>.
- [38] A. Kapałka, G. Fóti, C. Comninellis, *Determination of the Tafel slope for oxygen evolution on boron-doped diamond electrodes*, Electrochemistry Communications, 10, 607 (2008); <https://doi.org/10.1016/j.elecom.2008.02.003>.

- [39] C. Wan, Y. Ling, S. Wang, H. Pu, Y. Huang, X. Duan, *Unraveling and resolving the inconsistencies in tafel analysis for hydrogen evolution reactions*, ACS Central Science, 10(3), 658 (2024); <https://doi.org/10.1021/acscentsci.3c01439>.
- [40] M.C. van Ede, U. Angst, *Tafel slopes and exchange current densities of oxygen reduction and hydrogen evolution on steel*, Corrosion Engineering, Science and Technology, 59, 39 (2024); <https://doi.org/10.31224/3331>.
- [41] M.H. Santana, L.A. De Faria, J.F. Boodts, *Electrochemical characterisation and oxygen evolution at a heavily boron doped diamond electrode*, Electrochimica acta, 50, 2017 (2005); <https://doi.org/10.1016/j.electacta.2004.08.050>.
- [42] L. Janssen, M. Blijlevens, *Electrochemical oxidation of iodate to periodate*, Electrochimica acta, 48, 3959 (2003); [https://doi.org/10.1016/S0013-4686\(03\)00535-8](https://doi.org/10.1016/S0013-4686(03)00535-8).
- [43] F. Beck, H. Krohn, W. Kaiser, M. Fryda, C. Klages, L. Schäfer, *Boron doped diamond/titanium composite electrodes for electrochemical gas generation from aqueous electrolytes*, Electrochimica acta, 44, 525 (1998); [https://doi.org/10.1016/S0013-4686\(98\)00115-7](https://doi.org/10.1016/S0013-4686(98)00115-7).
- [44] M. Panizza, G. Cerisola, *Influence of anode material on the electrochemical oxidation of 2-naphthol: Part 1. Cyclic voltammetry and potential step experiments*, Electrochimica Acta, 48, 3491 (2003); [https://doi.org/10.1016/S0013-4686\(03\)00468-7](https://doi.org/10.1016/S0013-4686(03)00468-7).
- [45] R. Pawar, V. Subramanian, *Studies on the electrochemical oxidation of methanol using La_2MO_4 ($M = \text{Ni}, \text{Cu}$ and Zn) catalysts*, Catalysis Science & Technology, 15, 6678 (2025); <https://doi.org/10.1039/d5cy00827a>.
- [46] D. Santos, A. Lopes, M. Pacheco, A. Gomes, L. Ciriaco, *The oxygen evolution reaction at Sn-Sb oxide anodes: influence of the oxide preparation mode*, Journal of the electrochemical Society, 161(9), H564 (2014); <https://doi.org/10.1149/2.1031409JES>.
- [47] P. Yao, X. Chen, H. Wu, D. Wang, *Active Ti/SnO₂ anodes for pollutants oxidation prepared using chemical vapor deposition*, Surface and Coatings Technology, 202, 3850 (2008).
- [48] R. Kötz, S. Stucki, B. Carcer, *Electrochemical waste water treatment using high overvoltage anodes. Part I: Physical and electrochemical properties of SnO₂ anodes*, Journal of applied electrochemistry, 21, 14 (1991).
- [49] F. Vanzetti, H. Guzmán, S. Hernández, *Solid-State Reaction Synthesis of CoSb₂O₆-Based Electrodes Towards Oxygen Evolution Reaction in Acidic Electrolytes: Effects of Calcination Time and Temperature*, Catalysts, 15, 68 (2025); <https://doi.org/10.3390/catal15010068>.

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Структурні, оптичні та електрохімічні дослідження $\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ для застосування у суперконденсаторах

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$\text{La}_{0.8}\text{Sr}_{0.2}\text{CuO}_{3-\delta}$ одержано методом твердофазного спікання та досліджено його електрохімічні характеристики. X-променева дифрактограма після прожарювання за температури 950°C протягом 6 год відповідала орторомбічній фазі, при цьому додаткових дифракційних піків кристалічних фаз не виявлено. За даними сканувальної електронної мікроскопії (SEM) спостерігаються агломеровані частинки прямокутної форми із середнім розміром близько 0,4 мкм. Ширину оптичної забороненої зони (E_g) зразка визначали на основі спектра дифузного відбиття. Значення видимої оптичної забороненої зони, розраховане за графіком Тауца, становить 1,7 еВ, що свідчить про напівпровідниковий характер матеріалу. Зразок демонструє високе поглинання у видимій області спектра. Найвище значення питомої ємності за швидкості розгортки потенціалу 5 мВ/с становило 95,98 Ф/г. Кінетичний аналіз свідчить про переважання ємнісно-контрольованого механізму накопичення заряду ($\approx 71\%$ за 10 мВ·с⁻¹ зі зростанням до $\approx 88\%$ за 100 мВ·с⁻¹). Лінійна вольтамперометрія також вказує на активність реакції виділення кисню з потенціалом початку реакції 1,636 В та нахилом Тафеля 221 мВ·дек⁻¹. Перенапруга становить приблизно 444 мВ, 460 мВ та 470 мВ за густини струму 40, 50 та 60 мА·см⁻², відповідно.

Ключові слова: LaCuO_3 ; електрохімічні властивості; суперконденсатори.