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Investigation of Electrocatalytic behavior of mesoporous strontium selenide nanowires for hydrogen evolution reaction

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Summary

Tremendous efforts have been directed to synthesize electrocatalysts for hydro- gen evolution reaction but the electrocatalytic behavior of alkaline metal-based selenides has been rarely reported. Herein*,* SrSe nanowires have been synthe- sized using the solvo-hydrothermal process at various temperatures, and the synthesis has been confirmed using different techniques. The employed tem- perature affects the structure of the strontium selenides and has significantly influenced the hydrogen evolution reaction. Owing to the mesoporous nature and the greater specific and electrochemical surface area, the SrSe nanowires synthesized at 200◦C exhibit a greater number of active sites and show an over- potential of 127 mV to approach the current density of 10 mA cm—2 in 1 M KOH electrolyte. The SrSe nanowires also exhibit a greater turnover frequency of 41.20 ms—1 at the fixed reversible hydrogen electrode potential of 500 mV. The electrocatalyst SrSe nanowires reveal a Tafel slope of 135 mV dec—1, which is better than synthesis at other temperatures. The SrSe nanowires maintained the current density for 24 h chronoamperometry test in 1 M KOH electrolyte. The test results inspire further investigation and indicate the leading potential of SrSe nanowires for hydrogen evolution application.

KEYWOR DS

electrolytes, hydrogen evolution reaction, strontium selenide nanowires, Tafel slope, temperature

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# | INTRODUCTION

Incredible methodologies have been adopted to overcome the swelling energy crises, but unfortunately, these have produced the stern environmental problem.[1,2](#_bookmark26) The pro- duction of carbon dioxide from fossil fuels has seriously

twisted the general air and also has resulted in water pol- lution.[3-5](#_bookmark16) Therefore, pursuing clean energy resources has become a challenging task to balance the rapidly growing technology of the world.[6-8](#_bookmark17) Owing to abundance occur- ring, eco-friendly, high mass storage density, and long storage time, hydrogen has been considered a reliable

energy resource in the future.[9-11](#_bookmark18) Hydrogen energy has potential applications in various fields, such as for the production of steel, aluminum, and ammonia gas,[12](#_bookmark19) transport vehicles, to produce clean electricity, and hydro-treating of petroleum.[11,13](#_bookmark20) Hydrogen is an econom- ical and reliable resource. According to a report, the annual production of hydrogen energy is 44.5 million worldwide.[13](#_bookmark21) Hydrogen energy can be produced from sev- eral methods, that is, reforming of natural gas, solar tech- nologies, electrochemical water splitting and other fossil fuels with by-products of CO2.[14](#_bookmark22) Among these methods, the hydrogen energy from water splitting has been con- sidered the clean resource without any by-product.[15,16](#_bookmark23) However, the hydrogen production from electrochemical water splitting is only around 4% of total hydrogen pro- duction, while the remaining 96% of production consists of fossil fuel products.[17,18](#_bookmark24)

The efficiency of hydrogen production through water splitting depends upon the structure of the electrocata- lysts. Various electrocatalysts, for example, precious tran- sition metals like Platinum (Pt), Rhodium (Ru), Iridium (Ir), and Palladium (Pd),[19-21](#_bookmark25) polyaniline-based ZnS nanoparticles,[14](#_bookmark22) transition metal carbides,[22](#_bookmark27) nitrides,[23](#_bookmark28) oxides,[24](#_bookmark30) phosphides,[25](#_bookmark32) sulfides,[26,27](#_bookmark34) selenides,[28](#_bookmark37) tellurides,[29](#_bookmark40) MXenes, and perovskite electrocatalysts, have been fabricated to for the hydrogen production from water splitting. However, some factors such as environ- mental, cost, limited reserves, and stability of the electro- catalysts hinder the practical applications.[22,30-32](#_bookmark27) Perovskite materials have also been employed as electro- catalysts, but these are complex structures along with oxygen, and oxygen may hinder and occupy the active sites. MXenes are a new family of materials, and their synthesis is challenging. The synthesis of the MXenes is strongly dependent on the MAX phase and strong acids, usually, hydrofluoric acid.[33-35](#_bookmark44)

Tremendous efforts have been directed to synthesize the metal chalcogenides. Oxide has a sluggish reaction for the hydrogen evolution reaction (HER) process. Metal sulfides and selenides electrocatalysts have similarities but the Se-H bond has smaller energy as compared to S-H bonds, making the metal selenides suitable for the HER process. Moreover, sulfides show expansion and become oxidized in the atmosphere. The atomic radius of the Se element is greater than sulfur, which causes the decrease in ionization energy of selenium. Selenides exhibit greater electrical conductivity than sulfides due to selenium's metalloid nature.[19,36-38](#_bookmark25) Several attempts have been engaged to fabricate the selenide electrocatalysts for HER, but these are limited to transition metal-based sele- nides electrocatalysts, for example, indium-selenide,[39](#_bookmark29) nickel selenide nanostructures,[40](#_bookmark31) Ni-WSe2 nanostructures,[41](#_bookmark33) Fe-doped nickel selenide,[42](#_bookmark35) CoSe2,[43](#_bookmark36)

molybdenum selenide,[44](#_bookmark38) etc. Post-transition elements have also been incorporated with transition metal sele- nides for the HER process, that is, NiCoSxSey nanosheets,[45](#_bookmark39) Fe2PdSSe2,[46](#_bookmark41) nitrogen and phosphorus- doped cobalt selenides,[47](#_bookmark42) CoSe2/C,[48](#_bookmark43) etc. However, the alkali and alkaline metal-based selenides have not been explored effectively. Alkali and alkaline-based electrode structures exhibit good electrochemical characteristics for batteries and supercapacitor applications.[49-53](#_bookmark45) Owing to good electrochemical characteristics, alkali and alkaline- based electrode structures should be explored for the HER process to meet the challenges for commercial pur- poses. Usually, strontium exhibits the Sr+2 oxidation states and strontium-based materials exhibit high electri- cal conductivity, reactivity, and thermal and chemical stability. Moreover, strontium-based compounds have potential applications in various fields.[53-56](#_bookmark46) Hence, alka- line metal-based strontium selenides should also be explored as electrocatalysts for the HER process to meet the challenges of industries.

Furthermore, the impacts of the electrolyte are the

prerequisite to evaluating the performance of the electro- catalysts.[57-59](#_bookmark50) In this essence, the alkaline compounds in various electrolytes should also be considered and explored for the HER process until the existing problems of practical applications are solved. Strontium selenides- based electrocatalysts for the HER process have been found limited. In this work, several strategies have been adopted to explore the strontium selenide-based electro- catalysts for the HER process.

Herein, strontium selenide (SrSe) has been synthesized using the solvo-hydrothermal process at temperatures of 80◦C, 140◦C, and 200◦C for HER activity. SrSe nanopallets, hybrid of SrSe nanowires and nanopallets, and SrSe nano- wires were synthesized at 80◦C, 140◦C, and 200◦C, respec- tively. Detailed structural and morphological analyses have been performed, which reveals the successful synthesis of SrSe nanowires at 200◦C. HER activity has been evaluated in acidic (H2SO4, HCl), neutral (NaCl), and alkaline (KOH) electrolytes on nickel foam (NF) substrate. It is found that SrSe nanowires exhibit a good HER activity in 1 M KOH with an overpotential of 127 mV to approach the current density of 10 mA cm—2 and a Tafel slope of 135 mV on NF substrate.

# | EXPERIMENTAL SECTION

## | Chemical reagents

The chemical reagents include strontium nitrate (>99.5%, Sigma Aldrich), selenium powder (>99%, Macklin), hydrazine (>98%, Sigma Aldrich), H2SO4, HCl, NaCl

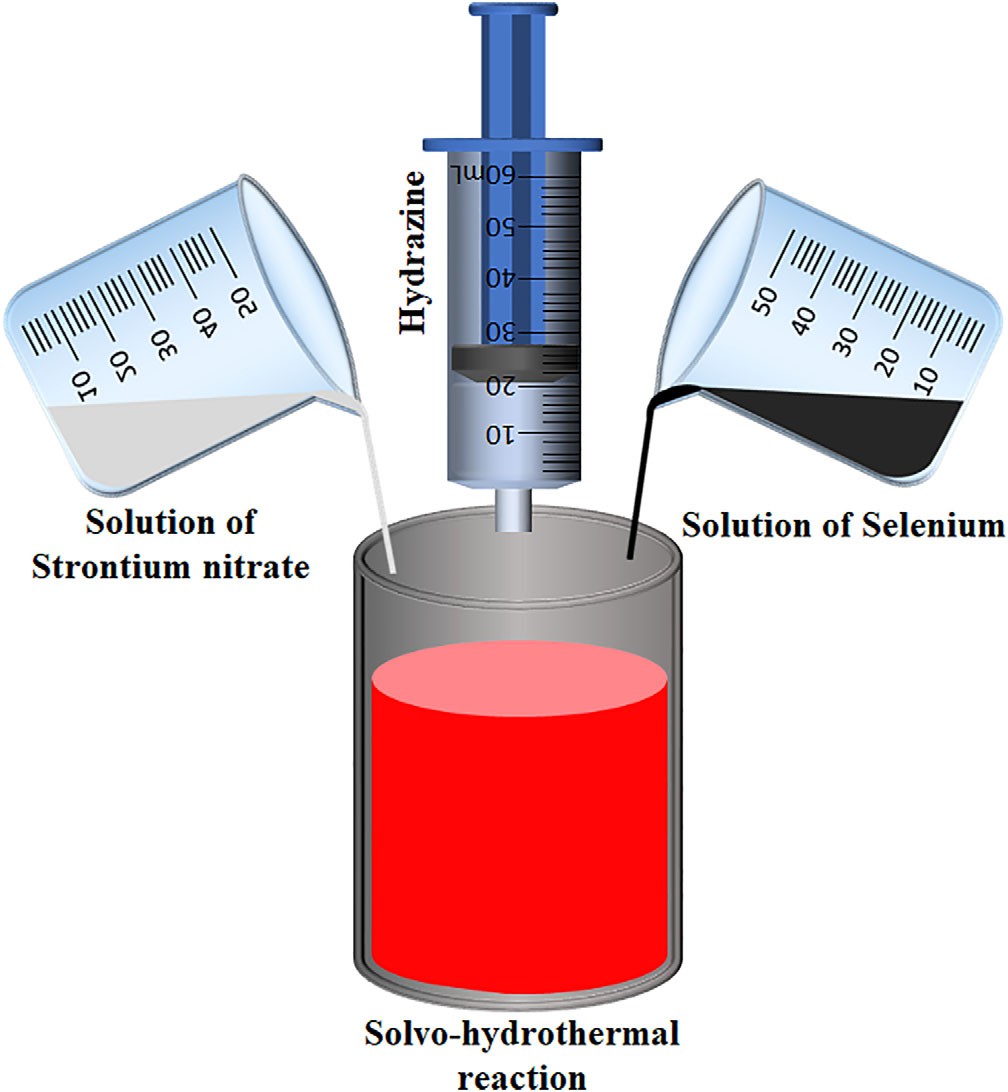


FIGURE 1 Schematic illustration for the synthesis of SrSe nanowires

(>99.5%, Sigma Aldrich), KOH (>99.5%, Sigma Aldrich), deionized water, autoclaves, and glass wares.

## | Synthesis of strontium selenide

Spectroscopy (XPS, AXIS SUPRA+), scanning electron microscope (SEM, Model-FEI Scios), high-resolution transmission electron microscope (HRTEM, Model-Talos F200s), and energy-dispersive X-ray spectroscopy (EDS, Model-Super-X EDS Detector). Specific surface area and pore diameter has been measured using the Brunauer Emmett Teller (BET, ASAP2460) technique.

## 2.4 | Electrochemical measurements for HER

HER was performed using the three electrodes system using the Zahner Zennium TR8M electrochemical worksta- tion. The three electrodes setup consists of a reference elec- trode (Ag/AgCl), a counter electrode (carbon rod), and working electrodes (prepared samples). The paste of the

electrocatalysts was prepared into 5 mL ethanol, Nafion as a binder (5 μL), and 2.2 mg of the sample and deposited on NF substrate (1 × 1 cm2). The prepared electrodes were

dried at 60◦C in an electric furnace for 24 h. Linear sweep voltammetry (LSV) was performed at the scan rate of

10 mV s—1, in to 5 mM H2SO4 (pH 2.5), 5 mM HCl (pH 2.9), 1 M NaCl (pH 7.2), and 1 M KOH (pH 13.90). The

cyclic voltammetry for the nonfaradaic area, the electro- chemical impedance spectroscopy, and the chronoampero- metry test were also performed for the HER process.

The overpotential was measured using the LSV data, which was transformed into reversible hydrogen elec- trode (RHE) potential using Equation ([1](#_bookmark7)),

◦

The solutions of strontium nitrate (0.8 M) and selenium powder (0.8 M) were prepared in 30 mL of deionized water into two separate beakers and the ultra-sonication was per-

*E*RHE

= *E*Ag/AgCl

+ *E*Ag/AgCl

+ (0.059 × *pH*), (1)

formed for 30 min at room temperature. After that, these solutions were mixed into an autoclave (100 mL) and 20 mL of hydrazine (35%) was added as a reducing agent using the syringe. The scheme has been illustrated in Figure [1](#_bookmark6). Similarly, a mixture of the solutions was prepared three times and the solvo-hydrothermal process was per- formed at 80◦C, 140◦C, and 200◦C in the same electric oven for 24 h. After completion of the reaction, products were washed and centrifuged with the mixture of ethanol and deionized water (500 mL, 1:1), 0.01 M HNO3 and again with deionized water and dried at 60◦C in a vacuum tube (OTF-1200X) for 36 h.

## | Characterization

The structure and morphology of the synthesized prod- ucts have been confirmed using the X-ray Diffractometer (XRD, Model-Rigaku Mini Flex 600), X-ray Photoelectron

where *E*Ag/AgCl and *E*◦Ag/AgCl were measured and the absolute thermodynamic potential of the Ag/AgCl elec- trode, respectively. The 0.059 is the correction faction for the specified pH of the electrolytes. The overpotential was measured at the state of art, the current density of 10 mA cm—2. The Tafel slope was measured from the lin- ear part from the potential vs RHE (V) and log of current density (mA cm—2) of LSV data, which satisfied Equation ([2](#_bookmark8)), and turnover frequency (TOF) was mea- sured using Equation ([3](#_bookmark9)),

η = a+ 2.303RT \* log *j*, (2)

αnF

TOF = *jA* , (3)

2*n* \* *F*

where F and n are, respectively, the Faraday constant (96 485 A s mol—1) and the involved number of electrons

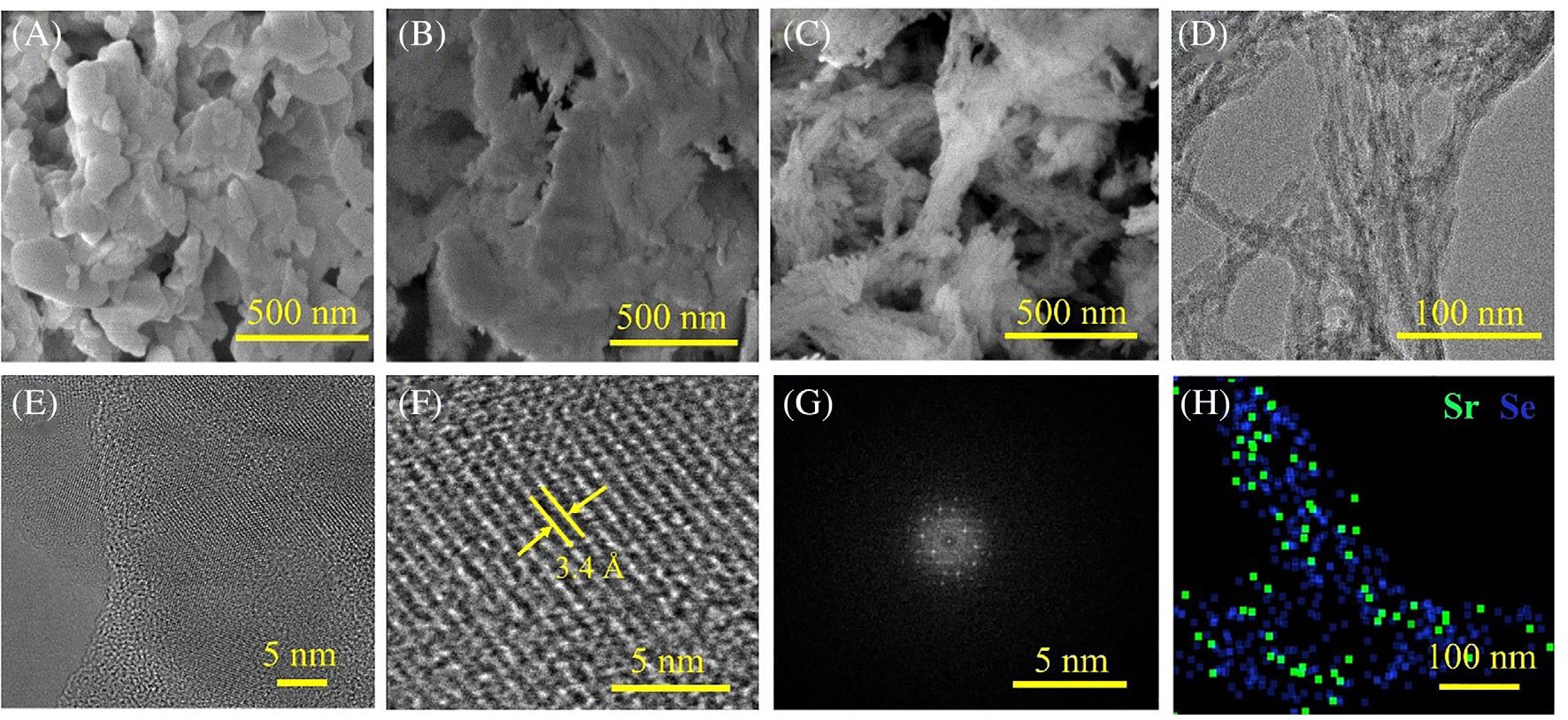


FIGURE 2 Scanning electron microscope images of (A) SrSe nanopallets, (B) hybrid morphology of SrSe nanowires and nanopallets,

(C) SrSe nanowires. (D, E) transmission electron microscope (TEM) images of SrSe nanowires, (F) interlayer spacing from the digital micrograph of highresolution TEM images of SrSe nanowires, (G) fast Fourier transform image, and (H) energydispersive X-ray spectroscopy mapping of SrSe nanowires

in the HER process, at the specified current density (j), and area of the NF substrate (A).Exchange current den- sity (Jexc) was calculated using Equation ([4](#_bookmark11)),

structure and HER activity. SEM reveals that the synthe- sis of SrSe at 80◦C exhibited a stack of interconnecting nanopallets-like morphology (Figure [2A](#_bookmark10)). The selenium powder showed the aggregates of cotton-like fibbers

*J*exc = RT nAFRct

, (4)

(Figure S1, detailed SI file). It can be concluded that SrSe was synthesized at 80◦C, slightly transformed from nano- fibers of selenium powder and the growth nucleation

where R and T are the universal gas constant and room temperature, respectively. Rct is the charge transfer resis- tance, which has been obtained from the Nyquist plot. The electrochemical surface area (*A*ECSA) was measured from non-Faradaic CV curves at various scan rates using Equation ([5](#_bookmark12)),[60](#_bookmark54)

*A*ECSA = *C*dl , (5)

*C*s

where *C*dl is the double-layered specific capacitance and *C*s is the general specific capacitance. The value of *C*s is in the range of 20–60 μF cm—2 for a flat area. In the pre-

sent case, a medium value of *C*s (40 μF cm—2) has been

used for *A*ECSA measurement.[61](#_bookmark56)

# | RESULTS AND DISCUSSIONS

Morphology plays an important role to evaluate the syn- thesis process and characteristics of the synthesized materials for energy storage and conversion devices. The morphologies of the SrSe synthesis at different tempera- tures were examined using the SEM to evaluate the

occurred in the horizontal plane. SEM images of SrSe at 80◦C reveal that the synthesis temperature affected the reaction and led to the change in morphology. The SrSe synthesis at a higher temperature of 140◦C, shows a dual shape, consisting of nanopallets and nanowires (Figure [2B](#_bookmark10)), which means, the growth process was influ- enced by the temperature and the growth nucleation occurs in both horizontal and vertical directions. When the temperature of the synthesis process increases to 200◦C, the morphology of SrSe was effectively changed showing the bundles of nanowires (Figure [2C](#_bookmark10)). The clus- ters and interconnecting nanowires of strontium sele- nides provided evidence of the temperature effects on the growth process. The nucleation of the precursors hap- pened in the vertical shape and led to the successful syn- thesis of the SrSe nanowires.

Morphology of SrSe has also been performed using the TEM and HRTEM along with EDS mapping. TEM and HRTEM images of SrSe at 80◦C and 140◦C have been shown in the SI file. TEM and HRTEM images of the SrSe nanowires synthesized at 200◦C revealed well- defined nanowires with a diameter of a few nanometers (Figure [2D-F](#_bookmark10)). HRTEM images of SrSe nanowires have been magnified using the digital micrograph software

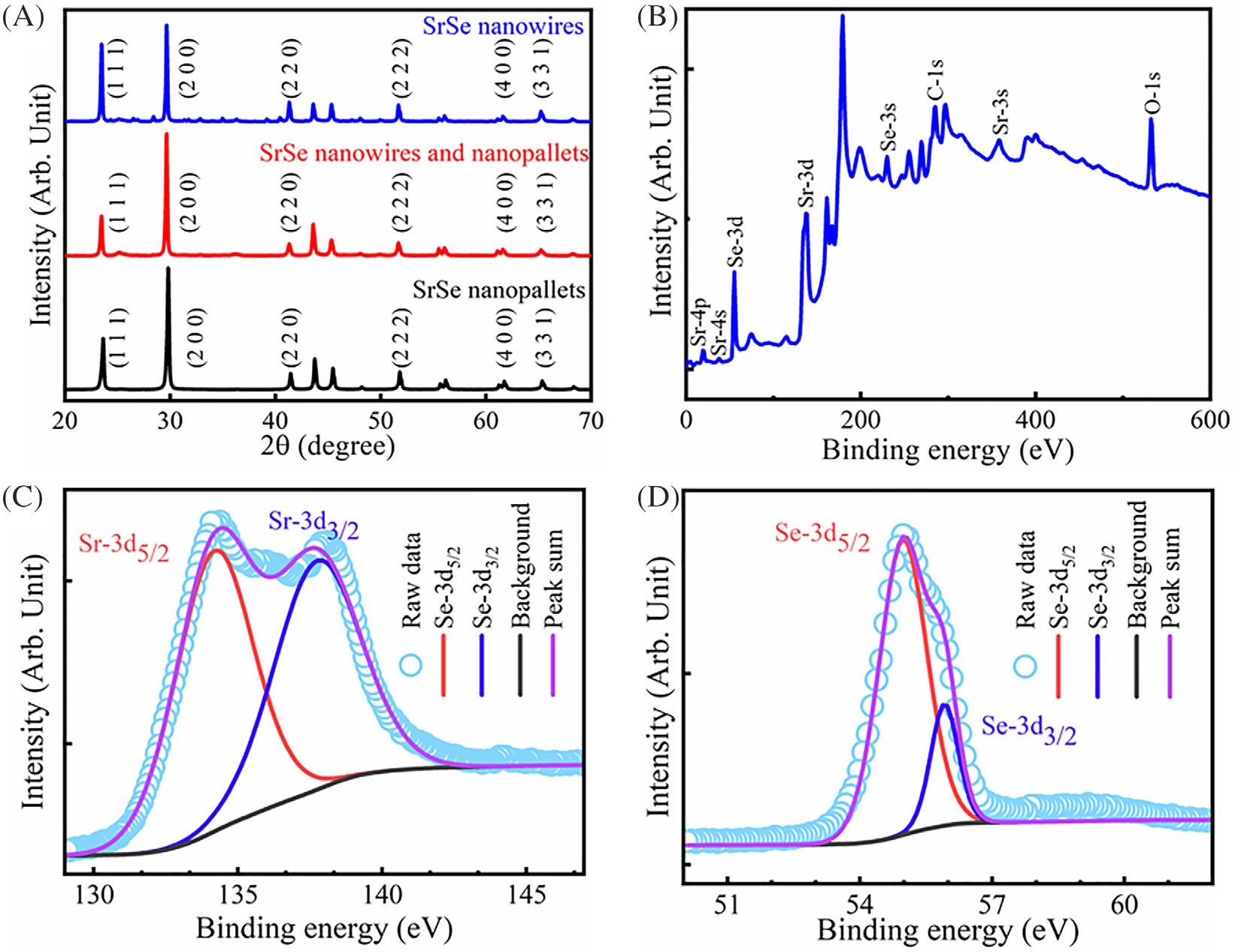


FIGURE 3 (A) Xray diffractometer pattern. (B) X-ray photoelectron spectroscopy (XPS) survey spectrum, XPS spectrum of

(C) strontium element, and (D) selenium element for SrSe nanowires

and the measured inter planner spacing is 3.4 Å (Figure [2F](#_bookmark10)), while the fast Fourier transform (FFT) image reveals the dominant crystal phenomena for SrSe nano- wires (Figure [2G](#_bookmark10)). The EDS mapping shows the uniform distribution of the strontium (green color) and selenium (blue color) atoms in the form of nanowires (Figure [2H](#_bookmark10)), which is consistent with the SEM, TEM, and HRTEM indications. The uniqueness in the morphology confirms the successful synthesis of SrSe nanowires at 200◦C.

The structural properties of the synthesized electroca- talysts SrSe were subsequently examined using the XRD. XRD patterns of SrSe synthesized at different tempera- tures are similar, and they exhibit some peaks at the

same position in 2θ angle (Figure [3A](#_bookmark13)) located at 23.60◦,

29.77◦, 41.48◦, 43.77◦, 45.60◦, 48.21◦, 51.85◦, 55.62◦,

56.14◦, 61.30◦, 61.82◦, and 65.44◦. However, some addi- tional peaks have been observed at 25.08, 26.45, 28.26,

31.61, 32.90, 34.97, 36.26, and 36.10, for SrSe nanowires synthesized at 200◦C, which provides evidence of the reactivity of strontium and selenium in SrSe nanowires. The peaks at 23.60◦, 28.26◦, 41.48◦, 51.85◦, 61.30◦, and

65.44◦ correspond to the planes (1 1 1), (2 0 0), (2 2 0),

(2 2 2), (4 0 0), and (3 3 1), respectively, which are well- matched with the JCPS card numbers of 98-005-3949 and 182 720, and reveal the cubic phase of strontium

selenides. Some peaks are not matched to the existed data for strontium selenide as the XRD data of the strontium selenides have been found very limited. However, the appeared peaks are well-matched with the cubic phase of the SrSe. The additional peaks may be due to some unknown phase of the strontium selenides, but the major peaks are identical to the cubic phase and provide evi- dence of successful synthesis of the SrSe nanowires.

Structural analysis was further confirmed using the XPS with Al Kα source and passing energy of 50 eV. The XPS data were analyzed using the CASAXPS software

and the binding energy of the elements was calibrated for compensation of the charge using the carbon energy C 1 s (284.8 eV).[62](#_bookmark58) The XPS survey spectrum (Figure [3B](#_bookmark13)) shows the coexistence of strontium (Sr-3 s, 4 s, 4p and 3d) and selenium (Se-3 s and 3d) elements, and confirms their reaction and the successful synthesis of SrSe nano- wires at 200◦C, (Figure [3B](#_bookmark13)).[63,64](#_bookmark60) The XPS spectrums for SrSe at 80◦C and 140◦C have also represented the co- existence of strontium and selenium (Figure S4). The XPS spectrum of SrSe at 80◦C shows the splitting of strontium at 134.10 and 138.58 eV, corresponding to Sr- 3d5/2 and Sr-3d3/2, while the energy peaks of selenium at

55.35 and 56.30 eV correspond to Se-3d5/2 and Se-3d3/2, respectively (Figure S4B,C). Similarly, SrSe synthesized at

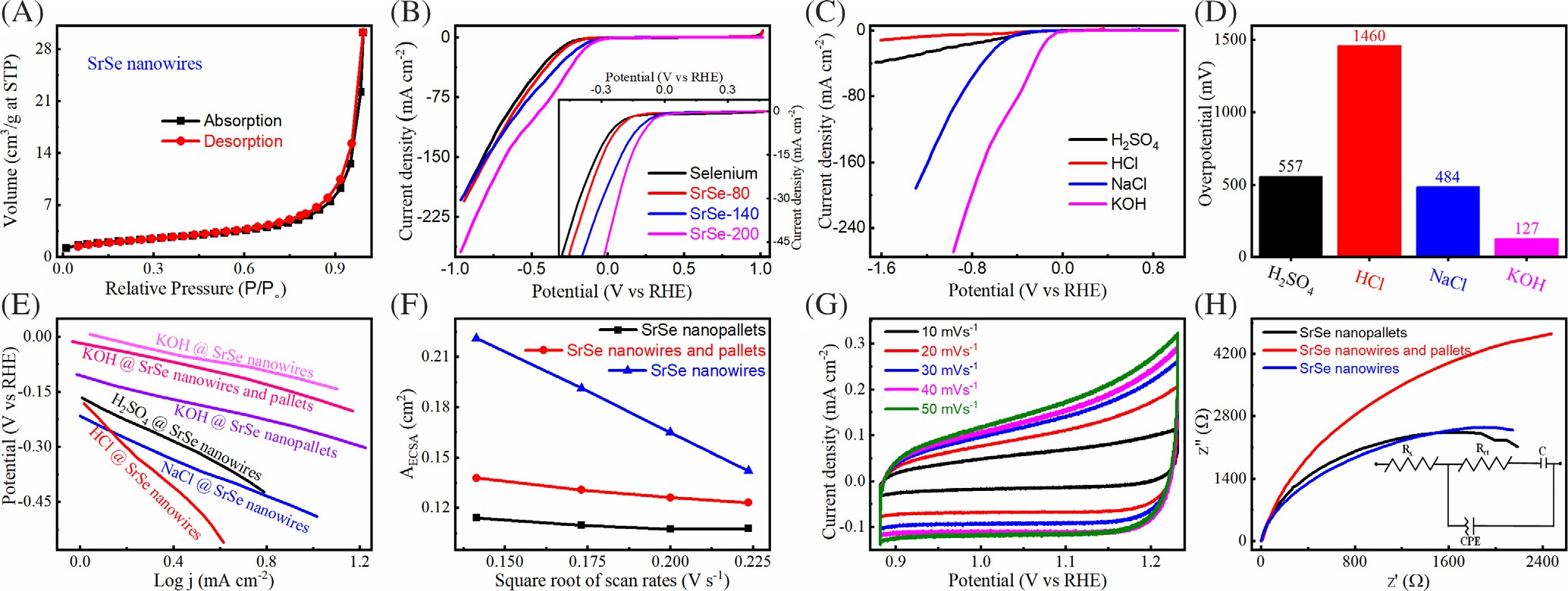


FIGURE 4 (A) N2 adsorption and desorption isotherm curves for SrSe nanowires (B) Comparative linear sweep voltammetry (LSV) curves in 1 M KOH (C) Comparative LSV curves of SrSe nanowires in various electrolytes (D) Comparison of overpotential of SrSe nanowires in various electrolytes (E) Tafel plots with corresponding medium and electrocatalysts (F) AECSA variations in 1 M KOH (G) Non- faradaic CV curves for SrSe nanowires, in 1 M KOH (H) Nyquist plot with the fitting circuit in 1 M KOH

140◦C also shows the splitting of strontium at 133.96 and

137.48 eV corresponding to the Sr-d5/2 and Sr-3d3/2, while the splitting of selenium at 54.67 and 55.30 eV corre- sponds to the Se 3d5/2, respectively (Figure S5C,D). The SrSe nanowires also showed the same behavior for the splitting strontium at 133.45 and 137.20 eV and the split- ting of selenium at 54.30 and 55.10 eV (Figure [3C,D](#_bookmark13)). The peaks split around 133.45 and 137.20 eV corresponding to the Sr-3d5/2 and Sr-3d3/2 states of strontium. The presence of Se-3d5/2 confirms the divalent nature of Se with a — 2 valence state.[64-66](#_bookmark62) The very minor shifting of the binding energy peaks may be due to hydrazine, the influence of temperature, or the incorporation of oxygen from the environment. Furthermore, the atomic ratio of strontium and selenium was found as 26.51% and 32.62%, respec- tively, in SrSe nanowires. The stoichiometric ratio of SrSe nanowires is also approximately 1:1. The successful reac- tion of divalent strontium atom with divalent selenium confirms the synthesis of SrSe structure.

The BET-specific surface area and pore volume of dif- ferent SrSe have been measured using the N2 adsorption– desorption isotherm curve. The N2 adsorption–desorption isotherm curves of SrSe nanopallets, hybrid of SrSe nano-

wires and nanopallets, and SrSe nanowires have been shown in Figure S5A, and Figure [4A](#_bookmark14), respectively. The related measured data have also been summarized in Table S1. The SrSe nanowires show a greater specific sur- face area of 7.63 m2g—1 and a total pore volume of

0.047 m3g—1 as compared to SrSe nanopallets and hybrid

of SrSe nanowires and pallets, which might be due to the unique morphology of SrSe nanowires. The pore diame- ter has been found in the range of mesoporous range and

suggests the mesoporous structure, with a larger specific surface area for SrSe nanowires, synthesized at 200◦C.

## | Hydrogen evolution reaction (HER)

The LSV of the electrocatalysts, including SrSe nanopal- lets, the hybrid of SrSe nanowires and nanopallets, and SrSe nanowires, has been performed in the potential win- dow of 0 and —2 V at the scan rate of 10 mV s—1. The obtained LSV data in various electrolytes (5 mM H2SO4, 5 mM HCl, 1 M NaCl and 1 M KOH) on NF substrate were converted into RHE potential. In all employed elec- trolytes, SrSe nanowires attained a greater current den- sity as compared to SrSe nanopallets and the hybrid of SrSe nanowires and nanopallets, which might be due to the greatest *A*ECSA and specific surface area of SrSe nano- wires (Figure [4B](#_bookmark14) and S4A-C).[67](#_bookmark64) The SrSe nanowires revealed the well-defined LSV curves in 1 M KOH elec- trolytes, as compared to other electrocatalysts, as pre- sented in the inset of Figure [4B](#_bookmark14). SrSe nanopallets and the hybrid of SrSe nanowires and nanopallets have been dis- cussed in SI file with details and the related measured values are summarized in Table S2.

The SrSe nanowires revealed a good HER activity and exhibited a greater current density during the LSV testing in 1 M KOH electrolyte as compared to other electrolytes (Figure [4C](#_bookmark14)). However, the electrocatalysts on NF show some instability and dissociation in a neutral medium, 1 M NaCl electrolyte. The electrocatalyst, SrSe nanowires produced strong bubbling and provided evidence of hydrogen evolution during LSV testing. The overpotential

is the first spine parameter to evaluate the HER activity of the electrocatalysts.[68](#_bookmark65) SrSe nanowires exhibited a good overpotential of 127 mV to approach the state-of-the-art current density of 10 mA cm—2, and showed the onset potential of —0.525 V/Ag/AgCl in an alkaline medium (1 M KOH), which is better than the HER activity in other electrolytes. The comparison of the overpotential in vari- ous electrolytes for SrSe nanowires has been given in Figure [4D](#_bookmark14) showing the significant difference in overpo- tential in different electrolytes. However, the perfor- mance of the SrSe nanowires is very poor in 1 m HCl electrolyte. SrSe nanopallets and the hybrid of the SrSe nanowires and nanopallets also showed a better overpo- tential in 1 M KOH electrolyte and the measured overpo- tentials have been summarized in Table S2. Hence, the role of the electrolytes is also dominant with the perfor- mance of the electrocatalysts for the HER process. The better overpotential of SrSe nanowires may be attributed to the greater specific surface area, mesoporous nature, and morphology at a temperature of 200◦C. Resultantly, the SrSe nanowires exhibited a greater number of active sites for the HER process. The intercalation of the elec- trocatalyst and the electrolyte (1 M KOH) ions was suit- able, which promoted the adsorption and desorption of the hydrogen ions at the active sites and improved the HER activity. The alkaline metal-based SrSe nanowires exhibited a good overpotential of 127 mV, which has been compared to the other electrocatalyst, especially, the selenides-based electrocatalyst at the same current density of 10 mA cm—2. The literature survey revealed that the overpotential of different electrocatalysts was observed as nickel cobalt selenide@118 mV in 1 M KOH,[45](#_bookmark39) Ag2Se@405 mV, WSe2@302 mV and Ag2Se/1 T- WSe2 nanosheets@140 mV in 1 M KOH,[69](#_bookmark66) NiSe2 nanosheets@197 mV and NiSe nanoflakes@217 mV in

0.5 H2SO4,[40](#_bookmark31) NiSe2/Ni3Se4/NF-1@185 mV and NiSe2/ Ni3Se4/NF-4@145 mV in 1 M KOH,[70](#_bookmark47) FeSe2@263 mV,

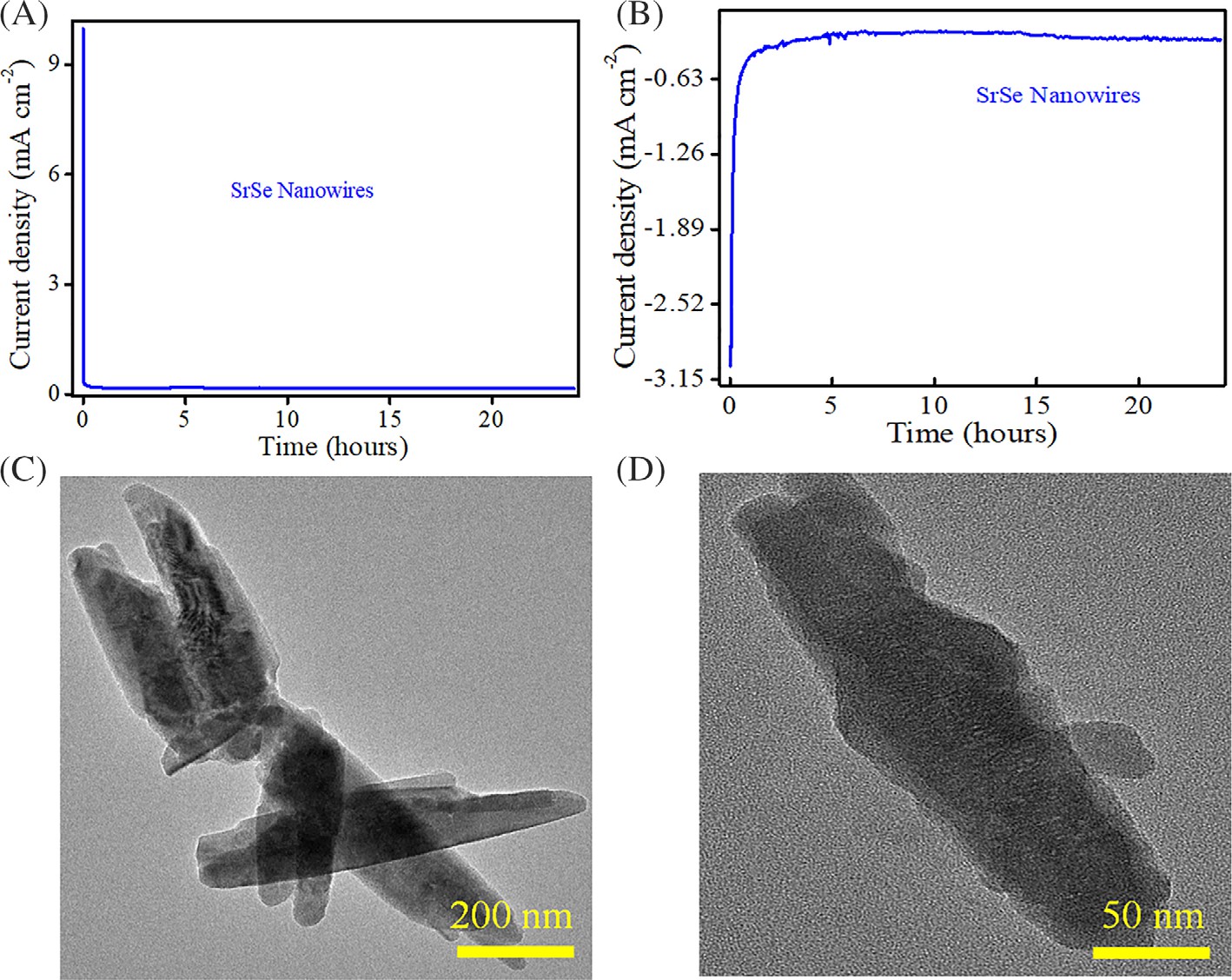
CoSe2@166 mV, and (Co,Fe)Se2@ 124 mV in 1 M KOH,[71](#_bookmark48) hollow CoSe2/MoSe2@168 mV in 1 M KOH,[72](#_bookmark49) MoSe2-ts@MoS2-ts@186 mV in 0.5 H2SO4,[73](#_bookmark51) MoSe2@170 mV in 1 M KOH,[74](#_bookmark52) Mo(S1—xSex)2@161 mV in 0.5 M H2SO4,[75](#_bookmark53) MoS2/SnS2@288 mV in 0.5 M H2SO4,[76](#_bookmark55) PyCoPc/GO-800@253 mV in 1 M KOH,[77](#_bookmark57) Ni-

WSe2@215 mV in 0.5 M KOH,[41](#_bookmark33) etc. The observation reveals that the performance of the simple of SrSe nano- wires is good and the comparative results will inspire the researchers to explore the alkaline metal-based electroca- talysts in detail for the HER process.

Tafel slope and TOF are the crucial parameters to eval- uate the HER activity of the catalysts.[78](#_bookmark59) SrSe nanowires exhibited the smallest Tafel slope of 135 mV dec—1 as com- pared to SrSe nanopallets (155 mV dec—1) and the hybrid of SrSe nanowires and nanopallets (156 mV dec—1) in 1 M

KOH. Owing to the good Tafel slope of SrSe nanowires in 1 M KOH, the Tafel slope of the SrSe nanowires was also measured as 318, 598 and 264 mV dec—1, in H2SO4, HCl and NaCl electrolytes, respectively, and the corresponding plots have been presented in Figure [4E](#_bookmark14). The Tafel slopes of the SrSe nanopallets and the hybrid of the SrSe nanowires and nanopallets have been measured and summarized in Table S2 and the corresponding plots are shown in Figure S6D. The Tafel slope of the SrSe nanowires was found better compared to other electrocatalysts in1 M KOH and revealed the fast HER activity. The smaller Tafel slope of the SrSe nanowires might be due to greater *A*ECSA and the number of active sites, which facilitated the adsorption and desorption processes of the active hydrogen atoms. The Tafel slope of the alkaline metal-based SrSe nanowires has also been compared with other selenides-based structures: Nickel cobalt selenide@144 mV dec—1 in M KOH,[45](#_bookmark39) Ag2Se@245, WSe2@254 mV dec—1 and Ag2Se/1 T-WSe nanosheets@125 mV dec—1 in M KOH,[69](#_bookmark66) pristine WSe2@152 mV dec—1 in 0.5 M KOH[41](#_bookmark33) and ReSe2 bulk @136.20 mV dec—1 in M KOH.[79](#_bookmark61) The comparative results show that the simply synthesized SrSe nanowires have potential applications HER process. The CV nonfaradaic curves were performed in 1 M KOH to measure the *A*ECSA of the electrocatalysts. SrSe nanowires exhibited the largest *A*ECSA at various scan rates, as compared to SrSe nanopal- lets and the hybrid of SrSe nanowires and nanopallets (Figure [4F](#_bookmark14)) in 1 M KOH. The *A*ECSA decreases linearly with the square root of the scan rates and measured *A*ECSA at various scan rates in 1 M KOH electrolyte has been sum- marized in Table S3. The nanofaradaic curves for SrSe nanowires in 1 M KOH at various scan rates are shown in Figure [4G](#_bookmark14), while the non-faradaic CV curves for SrSe nano- pallets and hybrid morphology of SrSe nanowires and pal- lets have been presented in Figure S6E,F. The good Tafel slope of SrSe nanowires is definitely due to greater AECSA, which exhibits the more active sites, promotes the transfer of electrons, and facilitates the HER process. Moreover, the nanowires-like structure controls the direction of the charge and increases the adsorption and desorption of the hydrogen atoms at the active sites, and, therefore, enhances the HER activity for SrSe nanowires. TOF was also mea- sured at the fixed RHE potential of 500 mV. The SrSe nano- wires show fast HER activity with a good TOF of

26.70 ms—1 in 1 M KOH electrolyte as compared to in other electrocatalysts and electrolytes (summarized in Table S2). EIS was also performed in the range of 0.1 to 105 Hz and the Nyquist plot from EIS data reveals that SrSe nanopallets and SrSe nanowires followed a similar trend, which was different from the hybrid of SrSe nanowires and nanopal- lets (Figure [4H](#_bookmark14)). They showed a smaller charge transfer resistance in alkaline 1 M KOH electrolyte as compared to other electrocatalysts. The charge transfer resistance (*R*ct)

FIGURE 5

(A) Chronoamperometry stability curve in forward biased in 1 M KOH

(B) Chronoamperometry stability curve after 190 d in revised biased in 1 M KOH. Transmission electron microscope images after 190 d and Chronoamperometry stability test at different resolutions (C) 200 nm and

(D) 50 nm for SrSe nanowires

was measured using the equivalent circuit (inset of Figure [4H](#_bookmark14)), which shows that the electrocatalysts exhibit the capacitive behavior and showed the same solution and charge transfer resistance, without the Warburg compo-

nent. The *R*ct was employed to measure the *J*exc. The mea- sured *R*ct was 0.796, 1.640, and 0.967 Ω and the *J*exc was 16.230, 7.830, and 13.300 mA cm—2, for SrSe nanopallets,

the hybrid of SrSe nanowires and nanopallets, and SrSe nanowires in 1 M KOH electrolyte, respectively. Moreover, the SrSe nanowires exhibited the smallest *R*ct of 0.967 Ω

with the largest *J*exc of 0.013 mA cm—2 in 1 M KOH, as

compared to other electrolytes. Furthermore, the EIS mea- surements of the SrSe nanowires in other electrolytes were

*R*ct of 34.800 Ω with *J*exc of 0.37 mA cm—2 in 1 M NaCl, Rct of 127 Ω with *J*exc of 0.10 mA cm—2 in 1 M HCl, and *R*ct of

38.80 Ω with *J*exc of 0.33 mA cm—2 in 1 M H2SO4. Thus, the

*J*exc current density was good in alkaline electrolyte, 1 M KOH, which might be due to the smooth flow of charge carriers and good intercalation of the electrolyte ion, which facilitates the conduction process for HER. The good HER activity in 1 M KOH electrolyte for SrSe nanowire may be attributed due to nanowires-like unique morphology, greater *A*ECSA and specific surface area, which facilitate the transport of charge carriers on soft NF substrate and enhanced the HER activity.[80,81](#_bookmark63)

The stability of the electrocatalyst is a fundamental and significant parameter for the evaluation of the HER activity. The stability of SrSe nanowires has been performed using chronoamperometry at 1.0 V in 1 M KOH electrolyte for 24 h. The current density got several seconds for

adjustment and after that exhibited the almost same cur- rent density for 24 h (Figure [5A](#_bookmark15)). The electrocatalyst exhib- ited the current density of 9.98 mA cm—2 earlier but abruptly dropped to 0.188 mA cm—2 until 0.724 h. The SrSe nanowires attained the current density of 0.176 mA cm—2 at 1.03 h and remained constant until 24 h. The stability test of SrSe nanowires has also been performed after 190 d, in a revised biased region at —1.0 V, in 1 M KOH electro- lyte for 24 h. The SrSe nanowires exhibited similar behavior in revised regions, and exhibited a greater current density of —3.04 mA cm—2 at earlier (Figure [5B](#_bookmark15)). However, the cur- rent density abruptly reduced and reached

—0.418 mA cm—2 at 1.21 h. The SrSe nanowires exhibited a lower current density of —0.238 mA cm—2 from a time interval of 8.6 to 14.20 h in the revised region. After that, the current density gradually increased to —0.275 mA cm—2 at 16 h and approached —0.292 mA cm—2 at the end of 24 h. The smoothness of current density even after 190 d of the test predicted the good stable nature of the electrocata- lysts consisting of SrSe nanowires. The greater number of TOF and *J*exc reveals that the SrSe nanowires are conduc- tive enough, stand for a long time without decay in the cur- rent density, and provide evidence of the stable structure.

Furthermore, the morphological stability of the elec- trocatalyst, SrSe nanowires has also been performed using the SEM and TEM of different magnifications and resolutions. The SEM images show the bundles of nano- wires, which are slightly dispersed in 1 M KOH during 24 h stability test but they maintain the nanowires-like shape (Figure S7). Moreover, the TEM images at different

resolution magnifications show the “soft” shape of nano- wires with a slightly greater diameter at the end of the stability test after 190 d (Figure [5C,D](#_bookmark15)). Hence, the electro- catalyst consisting of SrSe nanowires also exhibited a sim- ilar shape and morphology even after 24 h stability test after 190 d. The greater number of active sites at the suit- able synthesis condition and unidirectional morphology causes the smooth electrons transfer process and results in better HER activity of the SrSe nanowires. So, it can be concluded that SrSe nanowires can be an effective elec- trocatalyst for the hydrogen evolution process.

# | CONCLUSION

The SrSe nanowires have been successfully synthesized at 200◦C using the solvo-hydrothermal process. The growth nucleation of the precursors occurred in the verti- cal direction at 200◦C for the unique morphology of the nanowires with a large number of active sites inside the strontium selenide. The large AECSA, specific surface area, mesoporosity, and active sites jointly promoted the charge transfer for the HER process and the SrSe nano- wires reveal better HER activity in 1 M KOH electrolyte. The SrSe nanowires exhibit the overpotential of 127 mV to approach the current density of 10 mA cm—2 and a Tafel slope of 135 mV dec—1. The SrSe nanowires show a greater TOF of 41.20 ms—1 at the fixed RHE potential of 500 mV. The greater TOF and Jexc reveal that the meso- porous SrSe nanowires facilitate the adsorption and desorption of the hydrogen atoms at the inside active sites and enhanced the HER reactivity in the 1 M KOH electrolyte. The electrocatalyst, SrSe nanowires also maintain the current density for 24 h providing evidence for the stable structure. Hence, the alkaline metal-based SrSe nanowires can be an effective electrocatalyst for HER. The test results will inspire the researchers to explore more about alkaline-based electrocatalysts.

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CONFLICT OF INTEREST

All authors have participated in this manuscript and have no conflict of interest.

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