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## **SnO<sub>2</sub> modified CsH<sub>2</sub>PO<sub>4</sub> (CDP) protonic electrolyte for an electrochemical hydrogen pump<sup>†</sup>**

Minal Gupta,<sup>a</sup> Kangkang Zhang<sup>ab</sup> and Kevin Huang<sup>ID \*a</sup>

CsH<sub>2</sub>PO<sub>4</sub> (CDP) is a well-known super-protonic conductor. However, it must operate under high humidity conditions to prevent dehydration and fast conductivity decay. Herein, we report that adding hydrophilic SnO<sub>2</sub> into CDP can suppress the rate of dehydration of CDP, thus stabilizing protonic conductivity over a broader range of water partial pressures ( $p_{\text{H}_2\text{O}}$ ). A total of seven compositions of  $(1 - x)\text{CDP}/x\text{SnO}_2$  were prepared, where  $5 \leq x \leq 40$  (wt%), and examined for their phasal, microstructural, and vibrational properties using X-ray diffraction, field emission scanning electron microscopy, and Raman spectroscopy. The signature of H<sub>2</sub>O retained in SnO<sub>2</sub>-added CDP was confirmed by Fourier transform infrared (FTIR) spectroscopy. Among these samples, 18 wt% SnO<sub>2</sub> in CDP stood out, showing a stable protonic conductivity of  $0.6 \times 10^{-2}$  S cm<sup>-1</sup> at 250 °C, even at 10% H<sub>2</sub>O. We also provide data from pre- and post-test characterization to facilitate the understanding of the observed stability improvement and degradation mechanisms. Finally, we show stable H<sub>2</sub> pumping performance of electrochemical cells with pure CDP and 18 wt% SnO<sub>2</sub>-CDP electrolyte and Pt/C electrode. Overall, 18 wt% SnO<sub>2</sub>-CDP is the best composition, showing stable conductivity under reduced H<sub>2</sub>O conditions and 18 wt% SnO<sub>2</sub>-CDP electrolyte with Pt/C electrode is the best membrane electrode assembly (MEA) for electrochemical H<sub>2</sub> pumping for lower water partial pressure applications.

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## 1. Introduction

Solid acid electrolytes (SAEs) exhibiting high protonic conductivity are of great interest for electrochemical devices such as fuel cells, electrolyzers, and H<sub>2</sub> pumps.<sup>1–4</sup> A representative family of SAEs has a general formula of M<sub>x</sub>H<sub>y</sub>(AO<sub>4</sub>)<sub>z</sub>, where M = Cs, Na, Rb, NH<sub>4</sub>, K, and Li; A = P, S, As, and Se, and x, y, and z are numerals.<sup>5,6</sup> Among these solid acids, CsH<sub>2</sub>PO<sub>4</sub> (CDP) containing PO<sub>4</sub> tetrahedra exhibits the highest proton conductivity.<sup>7–9</sup> At 230 °C, CDP transforms from a monoclinic to a cubic phase (also known as the super-protonic phase), triggering gigantic increases in proton conductivity from 10<sup>-6</sup> S cm<sup>-1</sup> to 10<sup>-2</sup> S cm<sup>-1</sup>.<sup>9</sup> This super-protonic phase is stable up to 250 °C, after which it starts to gradually lose conductivity due to dehydration causing the phase change to less conductive Cs<sub>2</sub>H<sub>2</sub>P<sub>2</sub>O<sub>7</sub>.<sup>10,11</sup> Maintaining sufficiently high humidity to prevent dehydration is crucial for practical applications of CDP.

The higher the operating temperature, the higher humidity is required. Within 230–250 °C, a minimum of 35–38% H<sub>2</sub>O (or partial pressure of H<sub>2</sub>O,  $p_{\text{H}_2\text{O}}$ ) is needed to prevent dehydration of CDP.<sup>12–14</sup> In many practical applications, however, such a high H<sub>2</sub>O requirement limits the utility of CDP-based electrochemical devices.

To improve the stability of CDP under lower  $p_{\text{H}_2\text{O}}$ , mixing CDP with oxides or other protonic conductors has been attempted. For example, enhanced stability and conductivity of CDP were reported by adding 10 wt% cerium pyrophosphate (CeP<sub>2</sub>O<sub>7</sub>).<sup>15</sup> The addition of tin pyrophosphate (SnP<sub>2</sub>O<sub>7</sub>) to CDP was found to improve the low-temperature conductivity of CDP.<sup>16</sup> Similarly, the SiP<sub>2</sub>O<sub>7</sub>/CDP composite has also been used as an electrolyte for steam electrolysis,<sup>11</sup> H<sub>2</sub> separation of ammonia,<sup>17</sup> and fuel cells<sup>18</sup> with  $p_{\text{H}_2\text{O}} = 0.30\text{--}0.47$  atm. Apart from metal pyrophosphates (MP<sub>2</sub>O<sub>7</sub>), neodymium phosphate hydrate (NdPO<sub>4</sub>·xH<sub>2</sub>O) as a dopant was also found to improve both conductivity and stability of CDP by thermally stable hydrate water in NdPO<sub>4</sub>·xH<sub>2</sub>O.<sup>7</sup>

On the other hand, adding simple metal oxides into CDP has also been studied, but with conflicting results. For example, TiO<sub>2</sub> and SiO<sub>2</sub> have been found to stabilize CDP in sealed containers,<sup>12,13,15</sup> whereas, in another study, no stabilizing effect was observed by adding SiO<sub>2</sub> into CDP in either dry or

<sup>a</sup> Department of Mechanical Engineering, University of South Carolina, Columbia, South Carolina, 29208, USA. E-mail: huang46@cec.sc.edu

<sup>b</sup> Engineering Directorate, Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA

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humid environments.<sup>19</sup> It has been reported that adding  $\text{ZrO}_2$  into CDP in a molar ratio of CDP :  $\text{ZrO}_2 = 2 : 1$  improved the fuel cell performance at 275 °C and  $p_{\text{H}_2\text{O}} = 0.12 \text{ atm}$ .<sup>20</sup>

Despite the prior efforts to stabilize CDP at higher temperatures or at lower  $p_{\text{H}_2\text{O}}$ , none of them have been practically demonstrated. Searching for solutions/materials to stabilize the CDP phase and conductivity for practical applications is still in high demand. Here in this work, we report on the feasibility of using hydrophilic  $\text{SnO}_2$  as a stabilizer for conductivity.<sup>21–23</sup> A total of seven compositions of  $(1 - x)\text{CDP}/x\text{SnO}_2$  ( $x = 0 \leq x \leq 40 \text{ wt\%}$ ) were prepared and characterized using X-ray diffraction, field emission scanning electron microscopy, energy dispersive X-ray spectroscopy, and Raman spectroscopy, followed by electrochemical impedance spectroscopy (EIS) analysis on CDP– $\text{SnO}_2$  conductivity at 250 °C over a broad range of  $p_{\text{H}_2\text{O}}$ . The CDP– $\text{SnO}_2$  conductivity was particularly evaluated as a function of time at low  $p_{\text{H}_2\text{O}} = 0.10 \text{ atm}$ , at which pure CDP is known to be unstable. To understand the electrochemical behaviors and degradation mechanisms, post-tested samples were further analyzed by XRD, SEM, FTIR, and Raman spectroscopy. Subsequently, we performed chronoamperometry at 1 V under low  $p_{\text{H}_2\text{O}}$  conditions to acquire the electrochemical  $\text{H}_2$  pumping performance. The results of this study support the use of  $\text{SnO}_2$ -modified CDP-based membranes for hydrogen separation from various  $\text{H}_2$ -containing gas mixtures such as the products of water gas shift reaction as well as promoting hydrogenation/dehydrogenation reactions.

## 2. Experimental section

### 2.1. Sample preparation

Pure CDP was prepared using the co-precipitation method<sup>24</sup> where cesium carbonate ( $\text{Cs}_2\text{CO}_3$ , Alfa Aesar) and phosphoric acid ( $\text{H}_3\text{PO}_4$ , 85% purity, Sigma Aldrich) were used as a precursor in stoichiometric amounts. Initially,  $\text{Cs}_2\text{CO}_3$  and  $\text{H}_3\text{PO}_4$  were dissolved in 100 and 50 mL of methanol, respectively, and stirred in separate beakers for 2 hours to form transparent solutions. The solution of  $\text{H}_3\text{PO}_4$  was then poured into the  $\text{Cs}_2\text{CO}_3$  solution and stirred together for 5 hours to initiate the reaction  $2\text{H}_3\text{PO}_4 + \text{Cs}_2\text{CO}_3 \rightarrow 2\text{CsH}_2\text{PO}_4 \downarrow + \text{H}_2\text{O} + \text{CO}_2 \uparrow$ . Since the formed CDP is insoluble in methanol, it precipitates out as a solid. The precipitate was then filtered out and dried at 80 °C in an oven for 20 hours. The dried powder was mixed with methanol and then ball-milled for 6 hours. After drying, the final product was ready for use in characterization and testing. To prepare the composite of CDP and  $\text{SnO}_2$ , we simply mixed commercially available  $\text{SnO}_2$  powder (Fisher Scientific, mean size 2.71  $\mu\text{m}$ ) in the desired ratio as listed in Table 1 with the as-synthesized CDP in an agate mortar for 1 hour.

### 2.2. X-ray diffraction (XRD)

The phase compositions in the powder form of the pre- and post-tested electrolytes were examined with an X-ray diffractometer (Rigaku MiniFlex II) equipped with  $\text{Cu K}\alpha$  radiation

**Table 1** Compositions of CDP/ $\text{SnO}_2$  composite electrolyte in weight percent and molar ratio

Composite	Symbol	Weight% of $\text{SnO}_2$	Molar ratio (CDP : $\text{SnO}_2$ )
Pure CDP	CDP	0	1 : 0
95CDP : 05 $\text{SnO}_2$	CS-5	5	12 : 1
90CDP : 10 $\text{SnO}_2$	CS-10	10	6 : 1
86CDP : 14 $\text{SnO}_2$	CS-14	14	4 : 1
82CDP : 18 $\text{SnO}_2$	CS-18	18	3 : 1
75CDP : 25 $\text{SnO}_2$	CS-25	25	2 : 1
60CDP : 40 $\text{SnO}_2$	CS-40	40	1 : 1

( $\lambda = 1.5418 \text{ \AA}$ ) over a  $2\theta = 15\text{--}75^\circ$  range with a step size of  $0.02^\circ$  and a scanning rate of  $2^\circ \text{ min}^{-1}$ .<sup>25</sup>

### 2.3. Field emission scanning electron microscopy (FESEM) and energy dispersive X-ray spectroscopy (EDX)

Microstructures of fresh and post-tested composite electrolytes were characterized by a field emission scanning electron microscope (Zeiss FESEM with EDX) and elemental mapping was studied by energy-disperse X-ray spectroscopy (EDX) to analyze chemical composition.<sup>26</sup>

### 2.4. Raman spectroscopy

Raman spectroscopy was conducted using Horiba Jobin-Yvon LabRAM HR800 with a 532 nm excitation laser to investigate the vibrational properties of pure and composite pre- and post-test electrolyte samples.<sup>27</sup>

### 2.5. Electrical conductivity measurements

For the conductivity measurements, the symmetrical cell was constructed by sandwiching a uniaxially co-pressing CDP/ $\text{SnO}_2$  pellet with two identical carbon paper electrodes (Toray Carbon Paper 060 Value Pack, Wet Proofed, Fuel Cell Stores) at 300 MPa for 20 minutes. The area of each electrolyte was  $3.14 \text{ cm}^2$  (diameter = 20 mm) and thickness was maintained between 1.38 and 1.42 mm. Silver mesh and copper foam were used as current collectors. The experimental setup is illustrated in Fig. S1 (ESI†) and the actual parts used are shown in Fig. S2 (ESI†). EIS spectra were then gathered using a Solartron 1260/1287 electrochemical station within a frequency range of  $10^6\text{--}1 \text{ Hz}$  and an AC signal amplitude of 10 mV under open-circuit voltage (OCV) conditions. The highest-frequency intersection of the collected spectra with the real axis is the bulk resistance of the sample, from which the ionic conductivity was calculated. The experimental conditions include a constant temperature of 250 °C and a time of 12 hours in which  $p_{\text{H}_2\text{O}}$  started from 0.30 atm and decreased by 0.05 atm each time up to  $p_{\text{H}_2\text{O}} = 0.10 \text{ atm}$ . The  $\text{H}_2\text{O}$  partial pressure was controlled by a water bubbler at a specific temperature (see Table S1, ESI†), through which steam was provided using pure  $\text{H}_2$  as a carrier gas. To avoid steam condensation, all gas lines were covered with heating tapes at 100 °C.

### 2.6. Electrochemical pumping performance evaluation

For the electrochemical hydrogen separation, the membrane electrode assemblies (MEAs) were prepared by a co-pressing method at 300 MPa for 20 minutes, which uses Toray Carbon



Paper 060 Value Pack, Wet Proofed (Fuel Cell stores) as a support; Pt/C was 10% platinum on Vulcan 72 (Fuel Cell stores) as a catalyst, and naphthalene (Sigma Aldrich) in the electrode to make the electrode porous. The symmetrical MEA composition is as follows:

Carbon paper|CDP/SnO<sub>2</sub> + Pt/C + naphthalene|CDP/SnO<sub>2</sub>|CDP/SnO<sub>2</sub> + Pt/C + naphthalene|carbon paper. Roughly, 1 gram of the electrolyte and 0.1 gram of the electrode on each side were used in all MEAs to maintain a fixed thickness of 1.62 mm and active area of 3.14 cm<sup>2</sup> (diameter = 20 mm). Silver mesh and copper foam were used as current collectors.

The experimental setup for H<sub>2</sub> pump performance testing is shown in Fig. S3 (ESI<sup>†</sup>). Although we used the same cell fixture as the conductivity measurement with MEA as mentioned above, the gas supplies are different. In this case, one side of the electrolyte membrane was fed with 5%H<sub>2</sub>–N<sub>2</sub> as the H<sub>2</sub> source and another side of the electrolyte membrane was supplied with pure Ar to sweep out H<sub>2</sub>. The composition of H<sub>2</sub> + Ar was analyzed by online gas chromatography (Agilent MicroGC 490) for H<sub>2</sub> content, from which the H<sub>2</sub> rate, was derived. To ensure electrolyte stability, both 5%H<sub>2</sub>–N<sub>2</sub> and pure Ar were humidified to  $p_{H_2O} = 0.10$  atm levels through a water bubbler set at a specific temperature (47 °C). The constant DC voltage (1 V) was provided by a Solartron 1260/1287 electrochemical workstation. The rate of H<sub>2</sub> as a performance indicator was evaluated as a function of time at 250 °C and  $p_{H_2O} = 0.10$  atm for pure CDP and CS-18.

### 3. Results and discussion

#### 3.1. Phase composition of CDP/SnO<sub>2</sub> composites

The two-phase nature of CDP and SnO<sub>2</sub> was confirmed by XRD patterns as shown in Fig. 1(a). No extra impurity in the composite was observed. Two-phase Rietveld refinement (details for refined parameters are attached in Table S2, ESI<sup>†</sup>)<sup>28</sup> was also performed to confirm the mixture of CDP and SnO<sub>2</sub>. For this analysis, we considered *P21/m* (11) and *P42/mnm* (136) space groups for CDP and SnO<sub>2</sub>, respectively, and the refined pattern is shown in Fig. 1(b).

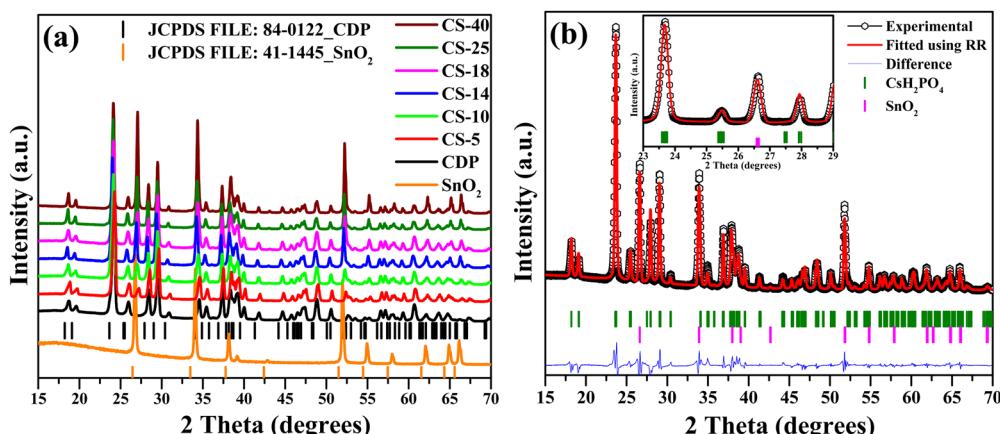


Fig. 1 (a) X-ray diffraction patterns of pure CDP and composite CDP/SnO<sub>2</sub> electrolyte. (b) Rietveld refinement patterns of CS-25 (75CDP: 25SnO<sub>2</sub>).

#### 3.2. SEM/EDX results

The cross-sectional view of a symmetrical cell consisting of a CDP/SnO<sub>2</sub> electrolyte and porous carbon paper-supported electrode is shown in Fig. 2(a). The bonding between the CDP/SnO<sub>2</sub> composite electrolyte and the electrode is reasonably good, showing no physical cracks or gaps between the two. In addition, Fig. 2(b) and (c) show that the CDP/SnO<sub>2</sub> electrolyte layer is dense in microstructure and uniform in elemental distribution. Fig. 2(d) further indicates the strong presence of Cs, Sn, and P in the composite membrane without other elements.

#### 3.3. Raman spectra

Raman spectroscopy is a powerful technique to detect lattice vibrations in chemical bonds.<sup>29–31</sup> To exploit this technique, we studied all the compositions; the results are shown in Fig. 3, in which the black and grey arrows indicate the Raman shifts for CDP and SnO<sub>2</sub>, respectively. All the shifts seen in pure and composite CDP and SnO<sub>2</sub> match well with those reported in the literature; no shifts other than those for CDP and SnO<sub>2</sub> were observed, which agrees with the XRD results.

The specification and assignment of each Raman shift in CDP and SnO<sub>2</sub> are listed in Table 2.<sup>32–34</sup> In the case of CDP, the wavenumber from 300 to 1250 cm<sup>–1</sup> is mostly related to the lattice vibration of O–P–O and P–O vibrations, whereas higher wavenumber lattice vibrations are dominated by O–H–O and O–H lattice vibrations. There are three types of O–H vibration in CDP: out-of-plane, in-plane, and stretching vibrations. Note that these lattice vibrational shifts may be affected during the test, which can be detected in post-test samples.

For the case of SnO<sub>2</sub> vibrations, the most intense peak belongs to Sn–O symmetric vibration at 631 cm<sup>–1</sup> and the intensity of this shift aligns linearly with SnO<sub>2</sub> addition in the CDP matrix, see the enlarged view in the inset of Fig. 3. Higher SnO<sub>2</sub> content leads to higher Raman intensity whereas lower intensity in the case of CS-5 and no SnO<sub>2</sub> shift in pure CDP. This indicates that, even with mechanical mixing, SnO<sub>2</sub> particles were properly incorporated into the CDP matrix forming a well-dispersed composite. Interestingly, some of the new shifts

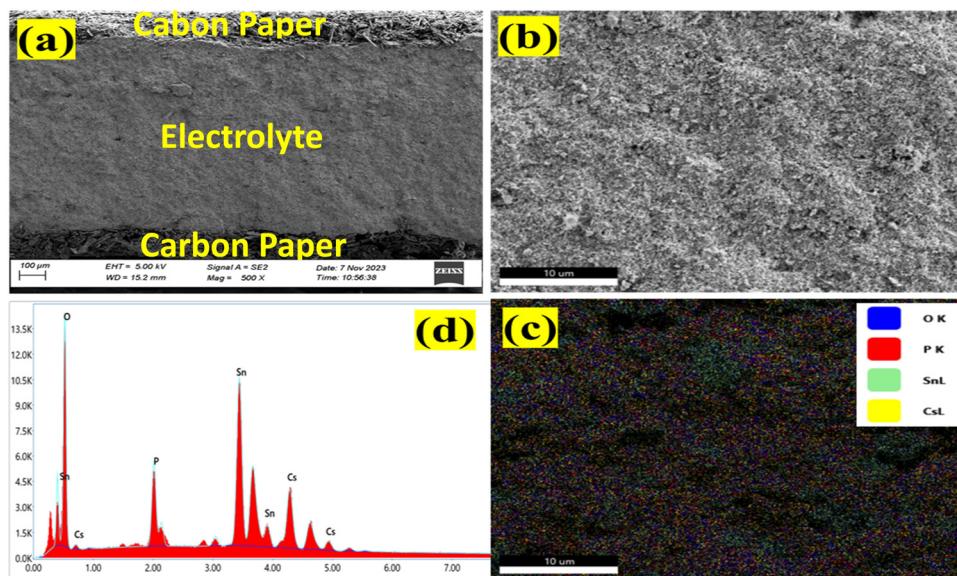


Fig. 2 (a) The cross-sectional view of CDP/SnO<sub>2</sub> sandwiched between carbon paper. (b) and (c) EDX of the CDP/SnO<sub>2</sub> composite electrolyte. (d) The elemental mapping of the CDP/SnO<sub>2</sub> composite electrolyte.

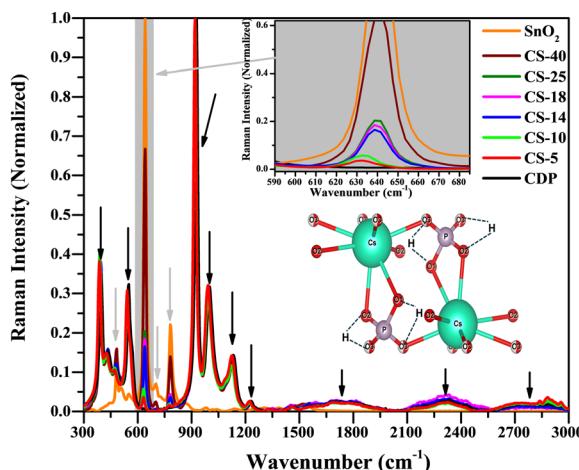


Fig. 3 Raman spectra of the CDP/SnO<sub>2</sub> composite electrolyte; the black arrow indicates shifts corresponding to CDP and the grey arrow indicates shifts related to SnO<sub>2</sub>. The representative crystal structure is extracted from VESTA software.

are observed in SnO<sub>2</sub>, implying the presence of nano-SnO<sub>2</sub> particles, see Table 2.

#### 3.4. EIS analysis

The evolution of ionic conductivity of pure CDP as a function of steam content at 250 °C is shown in Fig. 4(a). Up to 260 °C, CDP remains in the superionic phase and does not undergo phase decomposition.<sup>14</sup> At a high steam content of 30%, CDP exhibits a stable conductivity of  $1.5 \times 10^{-2}$  S cm<sup>-1</sup> for 12 hours. At a further decrease in steam content to 20%, only a small decrease is observed. However, a significant decrease in conductivity is seen at  $\leq 15\%$  steam by approximately one order of magnitude.

Table 2 Assignment and description of CDP and SnO<sub>2</sub> Raman shifts

Cesium dihydrogen phosphate (CsH <sub>2</sub> PO <sub>4</sub> ) (black arrow ↓ in figure)		
Wavenumber (cm <sup>-1</sup> )	Assignment	Description
389, 471, 561	A <sub>g</sub>	(OPO) skeleton bending vibrations
428, 550	B <sub>g</sub>	(OPO) skeleton bending vibrations
921, 1000, 1130, 1230	A <sub>g</sub>	(PO) skeleton stretching vibrations
1700	A <sub>g</sub>	Out-of-plane OH vibrations
2332	A <sub>g</sub>	In-plane OH vibrations
2750	A <sub>g</sub>	(OH) stretching vibrations

Tin oxide (SnO <sub>2</sub> ) (grey arrow ↓ in figure)		
Wavenumber (cm <sup>-1</sup> )	Assignment	Description
473	E <sub>g</sub>	Vibration of oxygen
631	A <sub>g</sub>	Symmetric Sn–O stretching
769	B <sub>2g</sub>	Asymmetric Sn–O stretching
510, 550, 700	New	Presence of nano-size SnO <sub>2</sub> particles

These results suggest that at least 20% steam is needed to ensure stable conductivity. A conductivity degradation mechanism for CDP under low steam content is dehydration, *i.e.* the material loses its ability to withhold H<sub>2</sub>O that is essential to conduct protons.

To minimize the steam dependence of CDP's conductivity, we selected SnO<sub>2</sub> as an additive to CDP; the former is known as a wide-bandgap super-hydrophilic material,<sup>21</sup> and its presence is expected to enhance the water-holding ability within CDP. The conductivity results of different CDP/SnO<sub>2</sub> compositions measured at 250 °C and 10% H<sub>2</sub>O are depicted in Fig. 4(b). A comparison with Fig. 4(a) indicates that CDP/SnO<sub>2</sub> composite electrolytes are more stable than pure CDP but with a lowered ionic conductivity to the magnitude of 10<sup>-3</sup> S cm<sup>-1</sup>. Taking the 7th-hour data in Fig. 4(b) for comparison purposes, Fig. 4(c) shows a peak conductivity at CS-18 composition. This is clearly

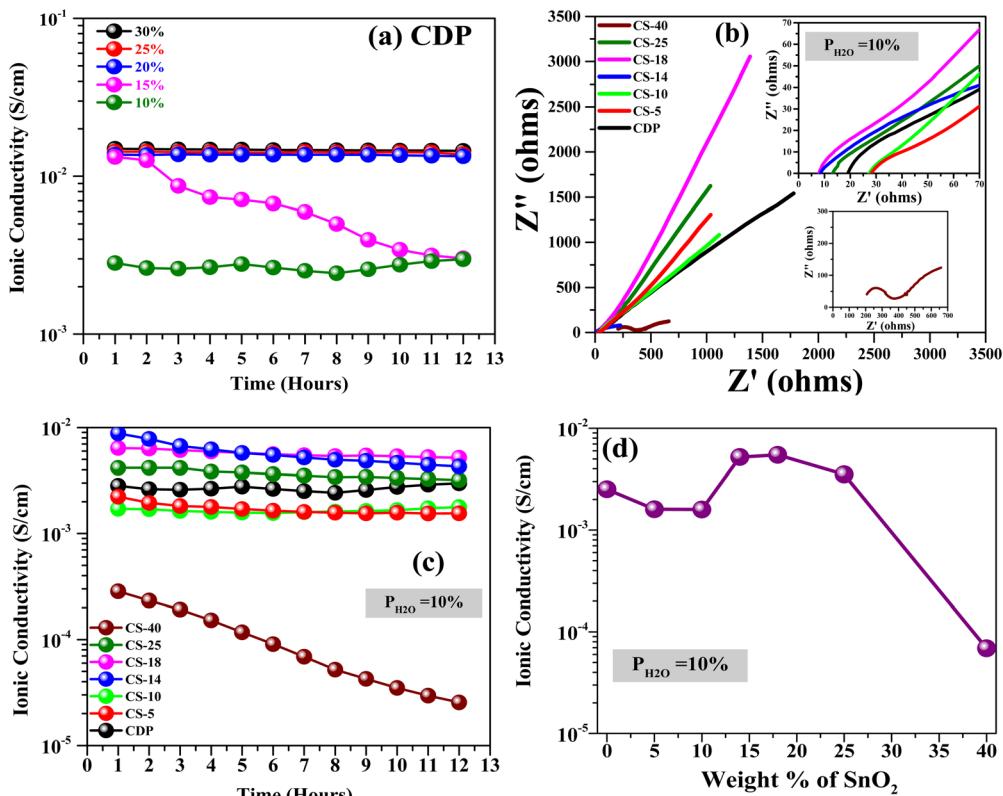


Fig. 4 (a) Time-dependent conductivity of pure CDP electrolyte at 250 °C in wet H<sub>2</sub> atmosphere at a 30 mL min<sup>-1</sup> flow rate on both sides and different water partial pressure. (b) Time-dependent EIS of the composite CDP/SnO<sub>2</sub> electrolyte at 250 °C in a wet H<sub>2</sub> atmosphere with 30 mL min<sup>-1</sup> flow rate on both sides and water partial pressure  $P_{H_2O} = 10\%$ . (c) Time-dependent conductivity of the composite CDP/SnO<sub>2</sub> electrolyte at 250 °C in a wet H<sub>2</sub> atmosphere with 30 mL min<sup>-1</sup> flow rate on both sides and water partial pressure  $P_{H_2O} = 10\%$ . (d) Variation in the conductivity (each at the 7th hour) of the CDP/SnO<sub>2</sub> composite electrolyte with respect to SnO<sub>2</sub> addition.

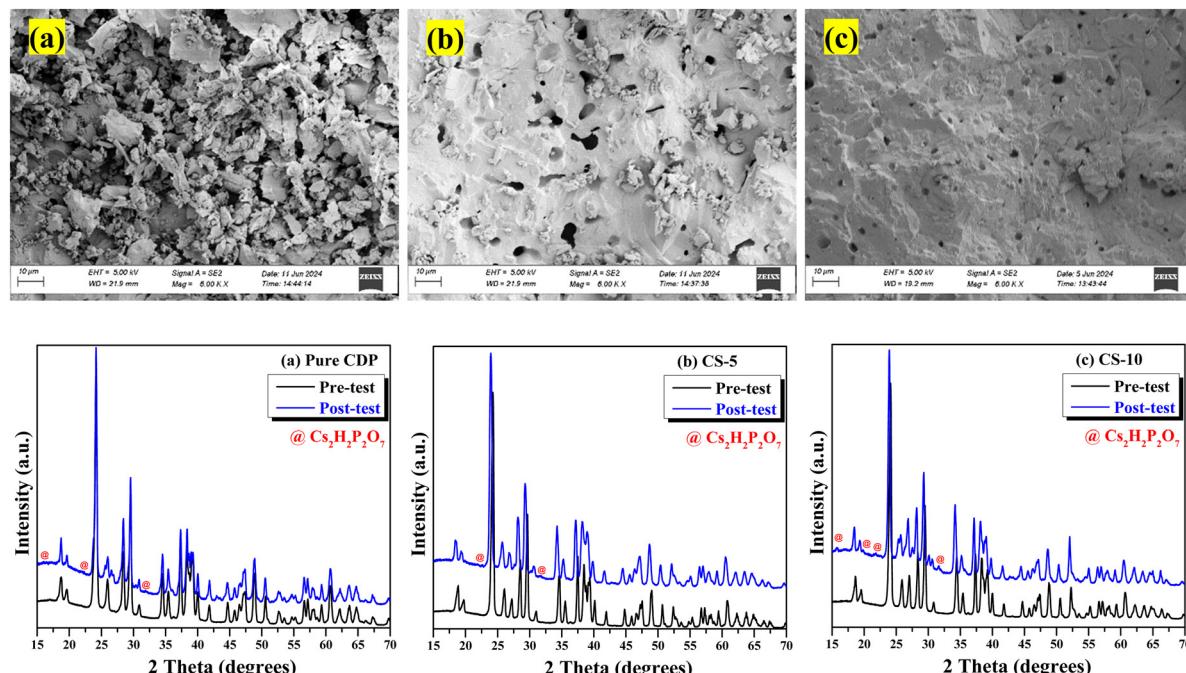


Fig. 5 Pre- and post-test FESEM (cross-sectional) and XRD data; (a) CDP, (b) CS-5, (c) CS-10.



the net result of the retained  $\text{H}_2\text{O}$  and blocked proton conduction in CDP by the presence of  $\text{SnO}_2$ .

**3.4.1. Lower  $\text{SnO}_2$  composite electrolytes.** Fig. 4(c) indicates that CS-5 and CS-10 exhibit a lower conductivity than pure CDP. To understand this abnormal behavior, we performed the post-test FESEM, XRD, FTIR, and Raman measurements on pure CDP, CS-5 and CS-10 samples. The microstructure of the post-tested CDP in 10% $\text{H}_2\text{O}$  is shown in Fig. 5(a) with a significant amount of porosity. These pores are left behind as  $\text{H}_2\text{O}$  in CDP and are lost from the body. As  $\text{H}_2\text{O}$  is lost, cubic CDP transforms to non-cubic  $\text{Cs}_2\text{H}_2\text{P}_2\text{O}_7$  with poor proton conduction. XRD patterns of the post-tested CDP in Fig. 5(a) support the above dehydration hypothesis. For CS-5 and CS-10, Fig. 5(b) and (c) of SEM images clearly shows fewer pores, suggesting that  $\text{SnO}_2$  addition helps in retaining the moisture content. The residual pores observed are likely derived from the dehydration of CDP particles. The corresponding XRD patterns of the tested CS-5 and CS-10 in Fig. 5(b) and (c) still show the decomposition products  $\text{Cs}_2\text{H}_2\text{P}_2\text{O}_7$ , implying that low  $\text{SnO}_2$  addition cannot stabilize the CDP electrolyte. The major cause for the low conductivity of CS-5 and CS-10 is the presence of the  $\text{Cs}_2\text{H}_2\text{P}_2\text{O}_7$  dehydration phase, which does not help in saving  $\text{H}_2\text{O}$  but allows faster dehydration, leading to fast conductivity decay as pure CDP. The  $p_{\text{H}_2\text{O}}$ -dependent study of CS-5 and CS-10 is shown in Fig. S4(a) and (b) (ESI†), which reveals that even higher  $p_{\text{H}_2\text{O}}$  does not stabilize the super-protonic phase with lower  $\text{SnO}_2$  loading.

**3.4.2. Moderate  $\text{SnO}_2$  composite electrolytes.** For the moderate compositions, CS-14 and CS-18, Fig. 4(d) indicates the highest protonic conductivity. To understand the underlying reason, FESEM imaging was carried out and the results are shown in Fig. 6(a) and (b). It is evident that the number and size of pores are significantly less than CS-5 and CS-10. More importantly, no initial dehydration phase of  $\text{Cs}_2\text{H}_2\text{P}_2\text{O}_7$  is found in the post-test XRD patterns, see Fig. 6(a) and (b) for CS-18 but in CS-14 only one sharp peak is noticed near 22.5 °C, probably due to slight dehydration. The suppressed dehydration of CDP by a moderate amount of  $\text{SnO}_2$  confirms our hypothesis that the hydrophilic (capability to hold water) nature of  $\text{SnO}_2$  can stabilize CDP even at low  $p_{\text{H}_2\text{O}}$ . To provide evidence of water withholding  $\text{SnO}_2$ , we performed FTIR on post-tested samples and the results are shown in the later section.

**3.4.3. Higher  $\text{SnO}_2$  composite electrolytes.** At the highest  $\text{SnO}_2$  content, CS-25 and CS-40, Fig. 4(d) indicate a decrease in conductivity, particularly for CS-40. Fig. 7(a) and (b) shows SEM images depicting the densest microstructure among all for CDP/ $\text{SnO}_2$  compositions; no pores were found. However, the XRD pattern shown in Fig. 7(a) and (b) indicates significant dehydration of CDP into  $\text{Cs}_2\text{H}_2\text{P}_2\text{O}_7$  and peaks of the secondary  $\text{SnP}_2\text{O}_7$  phase probably due to higher  $\text{SnO}_2$  content. Also noted is that the peak intensity of  $\text{SnO}_2$  surpasses that of CDP. Thus, a major cause for the loss of conductivity at higher  $\text{SnO}_2$  content could be the formation of secondary phases of  $\text{SnP}_2\text{O}_7$ , giving rise to a “conductor-insulator” type percolation effect.<sup>16</sup> The  $p_{\text{H}_2\text{O}}$ -dependent

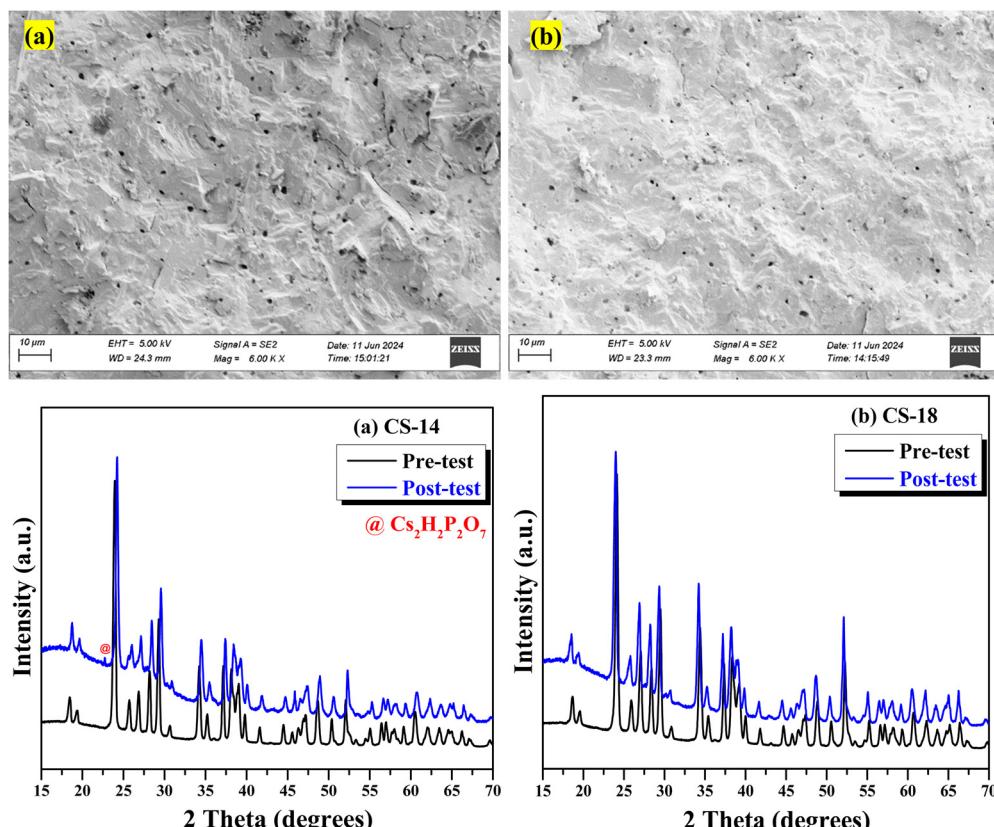


Fig. 6 Pre- and post-test FESEM (cross-sectional) and XRD data; (a) CS-14, (b) CS-18.



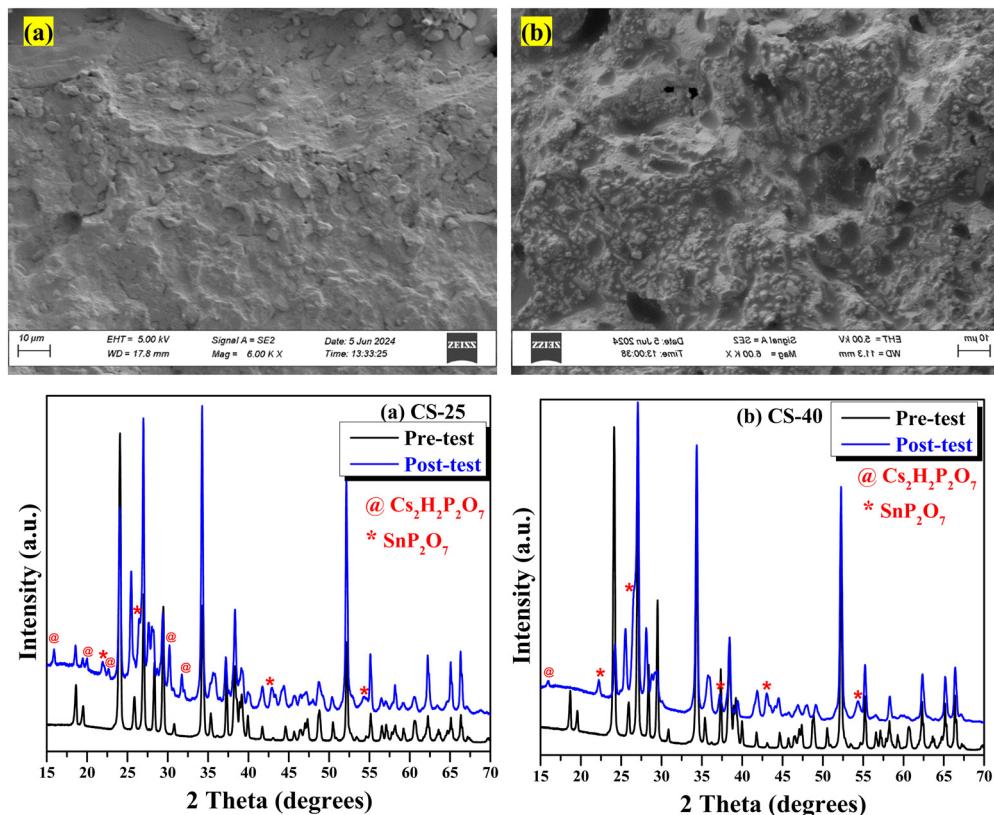


Fig. 7 Pre- and post-test FESEM images (cross-sectional) and XRD patterns; (a) CS-25, (b) CS-40.

study of CS-25 and CS-40 is shown in Fig. S4(c) and (d) (ESI†), which indicates that at higher  $p_{\text{H}_2\text{O}}$  (0.25–0.30 atm) can stabilize the CS-25 and CS-40 electrolytes but a decrease in the conductivity is observed for lower  $p_{\text{H}_2\text{O}}$ . Raman spectra (Fig. S5(a)–(g), ESI†) confirmed the XRD findings. Notably, the Raman intensity of (OH) vibrations does not change much in the CS-40 sample (Fig. S5(g), ESI†), which signals lower proton conduction and vanishing of  $\text{H}^+$  due to the formation of  $\text{SnP}_2\text{O}_7$ .

Overall, we have observed that  $\text{SnO}_2$  helps in stabilizing the CDP electrolyte at lower  $p_{\text{H}_2\text{O}}$ , and all compositions show stable conductivity greater than  $10^{-3} \text{ S cm}^{-1}$  at  $250^\circ\text{C}$  and 10%  $\text{H}_2\text{O}$ , except for CS-40. Among all the composites, for the CDP/ $\text{SnO}_2$  electrolytes discussed above, moderate  $\text{SnO}_2$  addition to CDP shows the best performance. Therefore, in the next section, we will further discuss the conductivities of CS-14 and CS-18 samples at  $250^\circ\text{C}$  as a function of  $p_{\text{H}_2\text{O}}$ .

### 3.5. Conductivities of CS-14 and CS-18 versus $p_{\text{H}_2\text{O}}$

Fig. 8(a) and (b) shows the measured conductivity evolution with time at  $250^\circ\text{C}$  under different  $\text{H}_2\text{O}$  contents. The conductivities of both the moderate  $\text{SnO}_2$  samples are higher at higher  $\text{H}_2\text{O}$ , but in general, become lower and less stable under lower  $\text{H}_2\text{O}$ . A close comparison of the conductivity values between the two samples in Fig. 8(c) at the 7th-hour marker shows a similar level at <20%  $\text{H}_2\text{O}$  but higher than that of pure CDP. At higher  $\text{H}_2\text{O}$  content, the differences among CS-14, CS-18 and pure CDP becomes indiscernible. Therefore, for fuel cell and  $\text{H}_2$  pump

applications with low  $\text{H}_2\text{O}$  feedstock, CS-18 is a better choice than pure CDP.

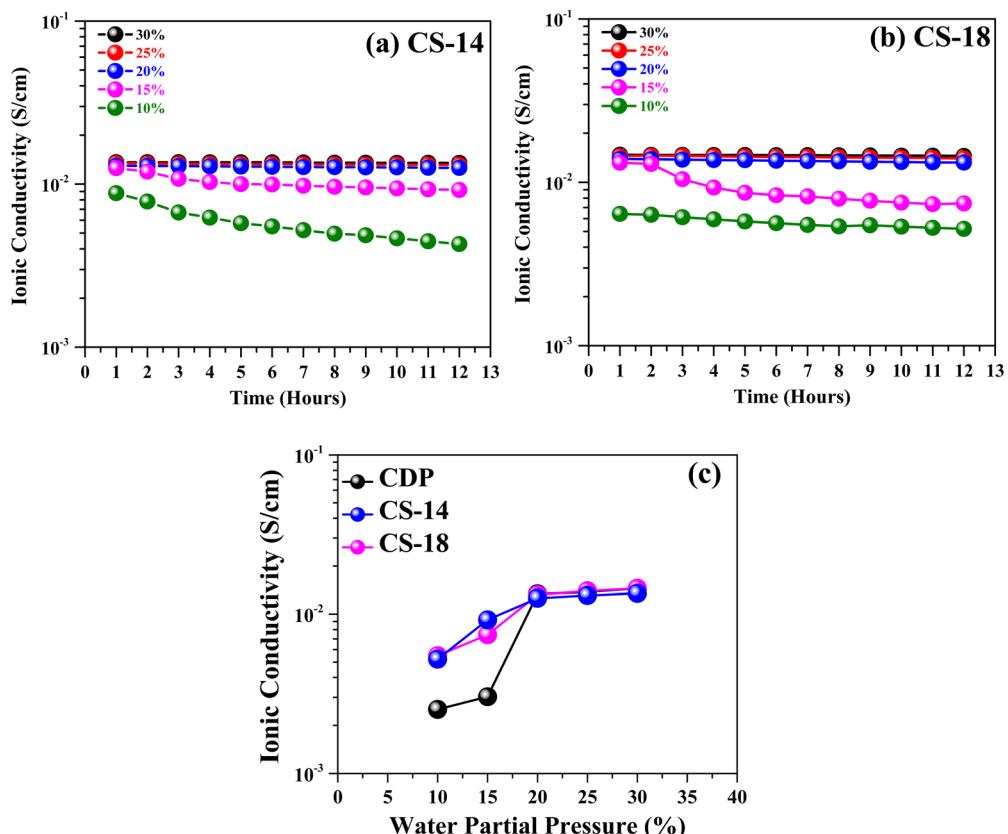
### 3.6. FTIR evidence of $\text{H}_2\text{O}$ and $\text{SnO}_2$ interaction

To understand the beneficial effect of  $\text{SnO}_2$  on retaining the stability of CDP, FTIR was carried out on pre- and post-test samples to probe the H and OH-bonding information; the results are shown in Fig. 9(a)–(h). For pure CDP, the vibrations related to the P–O are seen in the wavenumber range from 700–1250  $\text{cm}^{-1}$  (highlighted by grey color), whereas long and short O–H vibrations are observed above 1500  $\text{cm}^{-1}$  as indicated by the blue color arrow in all figures. For CDP/ $\text{SnO}_2$  samples, the FTIR spectra of the pre-test samples matched well with the pure CDP, and no new functional group was found. However, for the post-test samples, a new peak was observed between 3000 to 3500  $\text{cm}^{-1}$ . Based on the literature data, this peak can be assigned to water molecules bonded with  $\text{SnO}_2$  particles, generally denoted as Sn–OH.<sup>35</sup> Interestingly, the sample with moderate  $\text{SnO}_2$  loading (CS-14 and CS-18) exhibits the broadest peak compared to other compositions, implying the strongest Sn–OH interaction. The finding of the Sn–OH peak supports the assumption that hydrophilic  $\text{SnO}_2$  helps retain local water to stabilize CDP even at lower  $p_{\text{H}_2\text{O}}$ .

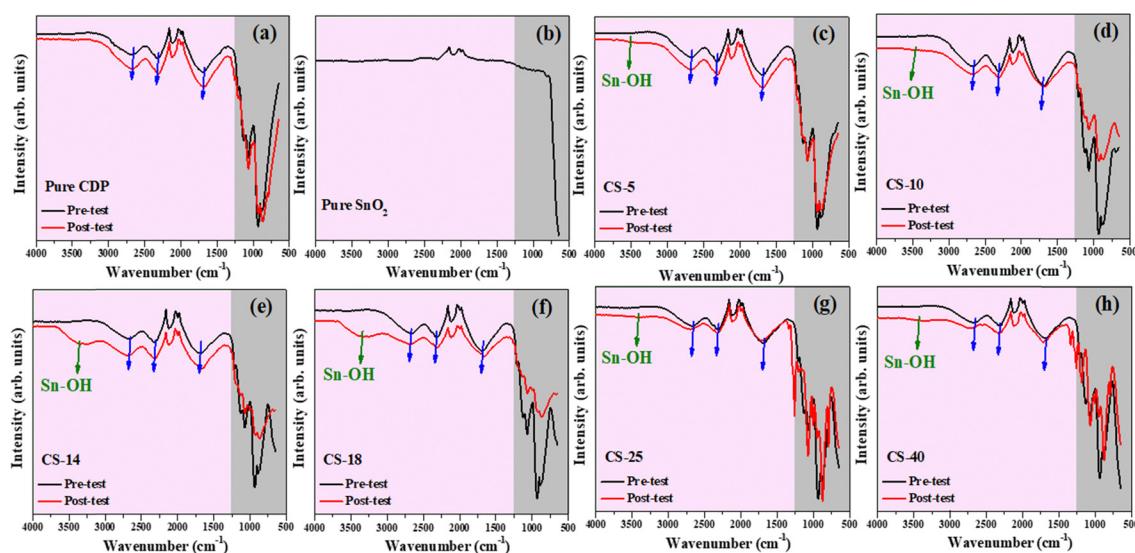
### 3.7. Electrochemical hydrogen pump performance

The CS-18 composition was selected as the electrolyte for our  $\text{H}_2$  pump testing as it showed the best stability compared to all





**Fig. 8** Time-dependent conductivity of composite electrolytes at 250 °C in wet H<sub>2</sub> atmosphere with 30 mL min<sup>-1</sup> flow rate on both sides at different water partial pressures: (a) CS-14 and (b) CS-18. (c) Comparative conductivities of CDP, CS-14, and CS-18 at different partial pressures.



**Fig. 9** (a)–(h) FTIR spectra for pure and composite CDP/SnO<sub>2</sub> electrolytes.

the other electrolyte compositions. To avoid the splitting of water that can occur above 1.23 V (ideally) due to the presence of external steam, we performed chronoamperometry at 1 volt with  $p_{\text{H}_2\text{O}} = 0.10$  atm to examine electrochemical H<sub>2</sub> pumping

performance at 250 °C for CS-18 and CDP electrolytes. Fig. 10(a) and (b) show variations in current densities and H<sub>2</sub> flux with time. For the CS-18 electrolyte, the pump current density and H<sub>2</sub> flux exhibit a slight decline before becoming flattened, while

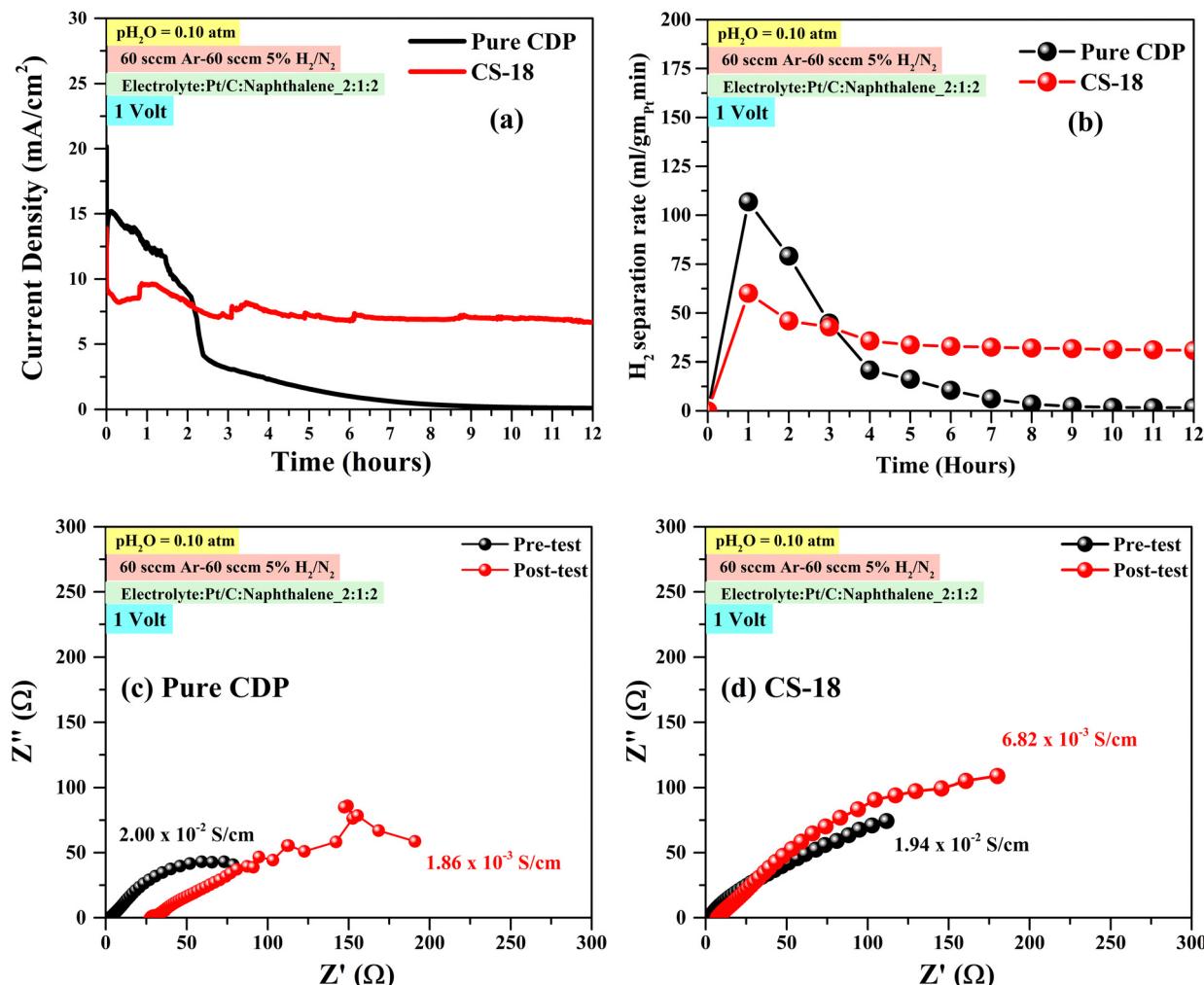


Fig. 10 (a) Chronoamperometry at 1 volt, 250 °C and  $p_{H_2O} = 0.10$  for CS-18 and CDP membrane. (b) The rate of  $H_2$  pumped at 1 volt. (c) and (d) EIS spectra of the pre- and post-test samples.

for the CDP electrolyte, the pump current density and  $H_2$  flux show a continuous decrease with time. Fig. 10(c) and (d) of EIS spectra suggest that the current/flux decline could be due to the decrease in the ionic conductivity of the electrolyte and electrode resistance for initial hours. Overall, we have demonstrated stable electrochemical  $H_2$  pumping performance using CDP/SnO<sub>2</sub> electrolytes at lower  $p_{H_2O}$ .

## 4. Conclusions

In this study, a range of hydrophilic SnO<sub>2</sub> mass was added into CDP to improve the conductivity stability of the latter. The conductivity results show that 18 wt% SnO<sub>2</sub> is the optimal content to achieve balanced conductivity and stability in CDP over a wider range of  $p_{H_2O}$ . At too low SnO<sub>2</sub> content, it is insufficient to suppress the dehydration of CDP at lower  $p_{H_2O}$ , thus causing conductivity decay. At too high SnO<sub>2</sub> content, on the other hand, it blocks the CDP protonic pathway by the formation of a secondary phase, thus significantly lowering the protonic conductivity. The signature of Sn-OH as an indicator

of water retaining ability of SnO<sub>2</sub> is confirmed by FTIR spectra in the post-tested SnO<sub>2</sub>-added CDPs. Overall, 18 wt% SnO<sub>2</sub>-added CDP represents a stability-conductivity balanced proton conductor that can potentially find applications in fuel cells, electrolyzers and  $H_2$  pumps. Subsequently, stable electrochemical  $H_2$  pumping performance is demonstrated with 18 wt% SnO<sub>2</sub>-added CDP electrolyte and Pt/C electrode at  $p_{H_2O} = 0.10$  atm. Overall, 18 wt% SnO<sub>2</sub>-CDP is the best composition with stable conductivity under reduced  $H_2O$  conditions and 18 wt% SnO<sub>2</sub>-CDP electrolyte with Pt/C electrode as the best membrane electrode assembly (MEA) for electrochemical  $H_2$  pumping for lower water partial pressure applications.

## Data availability

The data supporting this article are included as part of the ESI.†

## Conflicts of interest

There are no conflicts to declare.



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