YSZ/Polypyrrole hybrid nanostructure composite electrode for electrochemical double layer capacitor

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ABSTRACT

We have demonstrated a facile approach for synthesis of polypyrrole coated yttria partially stabilized zirconia nanocomposites by in-situ synthesis method. The properties of nanocomposite were studied and compared with those of polypyrrole and 8% YSZ. The electrochemical properties were recognized by cyclic voltammetry, charge-discharge and electrochemical impedance spectroscopy. The SEM of YSZ/PPy nanocomposite showed globular and porous surface morphology. In the present work, we reveal the YSZ/PPy nanocomposite as novel electrode material for supercapacitor. The supercapacitive performance of YSZ/PPy electrode was studied in an aqueous 0.1 N H2SO4 electrolyte solution. The highest specific capacitance (C_s) for YSZ/PPy electrode observed to be 640 Fg⁻¹. The specific energy (E_s), specific power (P_s) and coulomb efficiency (η%) are observed to be 12.8 Whkg⁻¹, 51 kWkg⁻¹ and 98% respectively. This electrode shows the outstanding electrochemical stability for more than 1000 continuous charging–discharging cycles. These notable parameters of YSZ/PPy composite opens up a new avenue for the study to explore this composite as an efficient electrode material.

keywords: YSZ, Hydrothermal synthesis, Charge-discharge, Electrode, Supercapacitor

Introduction

Intrinsically conducting polymers (ICPs) have been explored as promising materials in the sensory and energy storage applications. They emerged as a new class of materials with interesting electron–transport performance with colossal potential in scientific and technical applications. Most of the conductive polymers behave like p–type semiconductors due to delocalized electronic states which leads to the formation of a large energy gap. In the reported research work, the frequently used 9.5 mol % Yttria in Zirconia matrix stabilizes the cubic phase of zirconia. The cubic zirconia is solitary crystal which is optically clear form of ZrO₂ which has relatively low fracture toughness and strength. It has very high thermal shock resistance and chemically stable resulting in an excellent corrosion resistance. Partially Stabilized Zirconia (PSZ) is a cream coloured composite which has a very high strength. It is relatively cheaper in cost, characterised by high impact resistance and holds this property at high temperatures. Stabilizer stimulates a partial cubic crystal structure instead of fully tetragonal during initial firing which remains meta-stable during the cooling. Zirconia is frequently amalgamated either with magnesia, quicklime or yttria as a stabilizer in order to facilitate the toughness.

It is found that many researchers have been studied the composites of YSZ either with PPy or any other polymers to explore these composite for various applications. Vishnuvardhan et. al.⁴ reported the frequency dependent ac conductivity, dielectric loss of polypyrrole/Y₂O₃ composite and variation of dielectric loss as a function of mass % of Y₂O₃. Beatriz et. al.⁵ fabricated an energy storage device using porous 3% YSZ which acts as a separator and KOH as an electrolyte. Mudila et al.⁶ reported 17.13 Fg⁻¹ capacitance at 0.001 Vs⁻¹ for ZrO₂ in which zirconia/graphene oxide shows the enhanced most explicit capacitance of 299.26 Fg⁻¹ at the similar scan rate with power density of 59.40 W/kg. Ahmed et al.⁷ synthesized ZrO₂ nanofibers/activated carbon composite electrodes for the capacitive deionization units. He observed that the addition of ZrO₂ nanofibres distinctly enhanced the desalination process as the electrosorption capacity. Alves et al.⁸ showed the consolidation of rGO and zirconia nanoparticles in the PPy framework which transformed the morphology with the improved porosity enhancing the capacitance up to 100%. The rGO/ZrO₂/PPy supercapacitor gadget displayed a capacitance of 341 Fg⁻¹ and showed fantastic cycle life even after thousand cycles. He reported the enhancement in the specific capacitance from 143.1 Fg⁻¹ (pure PPy) to 200.1 Fg⁻¹ (PPy/rGO), and 143.1 Fg⁻¹ to 279.2 Fg⁻¹ for PPy/rGO/ZrO₂ electrodes.

In the present work, we report the maximum capacitance of 640 Fg⁻¹ for the composite made up of ceramic–core and conducting polymer scabard as YSZ/Polypyrrole electrode which we consider as a novel composite.
Experimental details

Chemicals
Pyrrole monomer (Sigma Aldrich) was double distilled before use. Zirconium nitrate [Zr (NO₃)₄], Iron (III) chloride hexahydrate, H₂SO₄, Yttrium nitrate [Y (NO₃)₃.6H₂O], Poly (ethylene oxide), Citric acid and Sodium lauryl sulphate were used of AR grade. All the aqueous solutions are prepared by using deionised water.

Synthesis of materials

Synthesis of PPy
The PPy was prepared as reported in Ref. 9. First pyrrole (1 M) was purified using double distillation before use. Then it was oxidized with Iron (III) chloride solution (2.4 M) under continuous stirring for 12 h. The reaction was carried out for 12 h at 0–5°C. After complete polymerization, the black precipitate of PPy was filtered under vacuum. Finally black powder of PPy obtained which was then dried at room temperature.

Synthesis of YSZ
The Yttria Stabilized Zirconia (YSZ) white powder was synthesized by hydro-thermal method. Zirconium nitrate and yttrium nitrate were mixed in beaker with stoichiometric ratio. Then citric acid was added as fuel to the above mixture of nitrate solution in a proportion of two moles per mole of metal ion. The above mixture was placed in a 250-mL teflon lined stainless steel autoclave. The three fourth of its volume was filled with mixture. The autoclave was heated at 200°C. for 8 h. Then it was air cooled to room temperature for 2 h. After hydro-thermal reaction, the samples were washed with deionized water for several times and dried in an oven at 100°C. After 2h, a fine white powder of YSZ was obtained which was further washed with water and ethanol to remove excess of impurity. Finally, it was dried at 60°C for 24 h in the oven.

Synthesis of YSZ/PPy
YSZ/PPy composite was prepared by in situ oxidative polymerization in an aqueous medium, as presented in figure 1. In continuation to the above procedure, the resulted ultra fine powder of YSZ was dispersed in 0.1 M Pyrrole-ethanol using 0.01 M sodium lauryl sulphate for 4h. Iron (III) chloride hexahydrate of 0.24 M was added slowly to the above mixture. The reaction bath was kept in ice bath between 0 to 5°C for 8h. After complete polymerization, the dense polypyrrole coated YSZ settle down at bottom in the reaction vessel and excess polymer float on the surface. The composite material was washed with the 50:50 deionised water/ethanol solutions to remove the unreacted monomer and oxidant. Finally, the powder was dried at 60°C for 24 h in an oven. In the synthesis of composites, we had attempted to set up the composite with the addition of 60% and 70% YSZ. We saw that in 60% and 70% addition of YSZ, the whole PPy was covered on certain pieces of YSZ particles, however the rest uncoated particles also stayed at the base (Table 1). These hybrid composite shows less conductivity. The composites above 50% YSZ addition didn’t show the normal expanding pattern of conductivity. Because of this explanation, we utilized 50% YSZ loading composite for further capacitor application.

Electrochemical measurements
The as-synthesised materials such as YSZ (1.25 gm) and YSZ/PPy (1.25 gm) were used for fabrication of electrode. High pressure of 980 MPA was applied on the powder to obtain a hard round pellet electrode. Poly (ethylene oxide) acts as an electrolyte separator which was used as sandwich-type construction like electrode/separator/electrode. The remaining side of the two electrodes were covered with silver paste act as current collectors to form double layer capacitor cell. The electrolyte was used on the separator before the use of cell. The performance of capacitor was observed using galvanostatic charge–discharge method at room temperature. The electrochemical measurements were carried out using a conventional three–electrode cell system. YSZ or YSZ/PPy composite electrode, standard calomel electrode (SCE) and platinum electrode were used as working electrodes, reference electrode and counter electrode respectively. 1 M H₂SO₄ solution was used as aqueous electrolyte. The potential window was kept constant and scan rate was varied as; 10, 20, 30, 50 and 100 mVs⁻¹. All potentials are reported with respect to the reference electrode. The measurements were calibrated using ferrocene as the standard at a scan rate of 10 mVs⁻¹. The EIS test was measured from 10 MHz to 100 MHz and amplitude was 5 mV versus open circuit potential.

Results and discussion

FT–IR analysis
The FT–IR spectra of YSZ, PPy and YSZ/PPy materials were captured using nano size powder. Figure 2 shows FT–IR spectrum of YSZ, PPy and YSZ/PPy materials. The characteristic absorption bands of polypyrrole are observed at 785, 923, 1043, 1170, 1390, 1552, 1640, 3439, 3749 and 3853 cm⁻¹. The fundamental bands of PPy related with symmetric and asymmetric ring stretching vibrations are observed in the range of 1542–1556 and 1455–1467 cm⁻¹ in YSZ/PPy composite. The slight shift
in their band position observed which is attributed to $\pi$ to $\pi^*$ electron stacking between pyrrole ring and oxidant. The major bands observed between 3432–3440 cm$^{-1}$ of PPy corresponds to stretching vibration of N–H bond in the composite. The presence of these bands confirms the polymerization of pyrrole and formation of the long–chain PPy. The peak observed between 1636–1638 cm$^{-1}$ is attributed to C=O. Thus, this peak may be strongly correlated to the interaction of carbon atom of the pyrrole ring and the oxygen atom of the oxidant. The characteristic symmetric deformations of NO$_3^-$ or CH$_3$ are observed at around 1384–1290 cm$^{-1}$. The bands at 1292–1300 cm$^{-1}$ and 1172 cm$^{-1}$ correspond to the N–H in-plane and C–H in-plane deformation modes are observed in composite with small shift. This attributes to the interaction of pyrrole ring with the oxidant.

X–H in-plane deformation of pyrrole ring is observed at 1043 cm$^{-1}$. The band at 782 cm$^{-1}$ is attributed to C–H out-of-plane bending observed in PPy as well as in composite$^{13}$. The absorption peaks at 785, 1052, 1390, 1552, 1640, 3439, 3749 and 3853 cm$^{-1}$ were observed in the YSZ/PPy nanocomposite due to the interaction of YSZ and PPy backbone. The C-H wagging vibration at 785 cm$^{-1}$, =C-H out-of-plane vibrations at 923 cm$^{-1}$, C-H in plane deformation at 1043 cm$^{-1}$ and C-N stretching vibration at 1170 cm$^{-1}$ were observed in PPy as well as in YSZ/PPy composite which are shifted towards a lower wave number. The IR peak obtained at 1043 and 923 cm$^{-1}$ are due to the =C–H out of plane vibration indicates the polymerization of pyrrole. The characteristic peaks found at 1552 cm$^{-1}$ and 1464 cm$^{-1}$ correspond to the C=C stretching, whereas the peak at 1314 cm$^{-1}$ represents to C–N bond. The N–H and C–H stretching vibrations of PPy are appeared at 3439 and 2929 cm$^{-1}$ respectively. The shifting as well as disappearance of some absorption bands is due to the composite formation. Finally, all fundamental bands of PPy are observed in YSZ/PPy composite which confirms the formation of desired composite material.

**SEM and EDS analysis**

In Figure 3, image (a, b) are the micro-graphs of the YSZ nanoparticles. Image (c, d) is the micro-graphs of PPy and image (e, f) represents the SEM of YSZ/PPy nanocomposites. The diameter of the globular YSZ particles observed between 40 nm to 50 nm. It is found that the particle size is almost uniform with the narrow distribution. In case of YSZ/PPy nanocomposites, agglomeration is present to same extent, but still globular particles can be seen clearly. The diameter of the YSZ/PPy nanocomposites found to 80 nm to 100 nm. As compared to the diameter of YSZ, the diameter of YSZ/PPy nanocomposite particle is increased due to the coating of PPy on YSZ surface (c, d). Elemental composition of YSZ/PPy nanocomposite was determined by EDS. The major elements in the nanocomposites are Y, Zr, carbon, nitrogen and oxygen. C, N, O are primarily associated with PPy (g). This morphological analysis revealed that the YSZ/PPy nanocomposite is formed.

**XRD analysis**

X–ray diffraction analysis results for PPy, YSZ and YSZ/PPy are displayed in Figure 4. Diffraction pattern for amorphous polypyrrole (PPy) gives characteristic broad-peak at 24°–27° 20 value. This broad peak in the spectrum is due to the scattering from materials at interplanar spacing. YSZ particles are observed with sharp diffraction peaks at 30, 34.6, 50.2, 59.98, 62.6 and 73.7 can be indexed as the (111), (200), (220), (311), (222) and (400) planes of crystalline structure$^{14,15}$. It can be clearly indexed to face centered cubic (fcc) structure of YSZ [JCPDS Card No. 48–0224]. However, all peaks of YSZ/PPy are broad at base but are in agreement to JCPDS data of YSZ material. XRD pattern for this composite also shows the characteristic peak of PPy which provides an additional evidence of the interaction between polymer and the YSZ particles. Due to crystalline nature of YSZ particles, more diffraction occurs in X–ray beam and the intensity of diffracted peaks is observed to be high. But in case of YSZ/PPy composites, the intensity of peaks seems to be decreased because of more absorption and less diffraction in X–ray beam due to polypyrrole shell, which supports formation of YSZ/PPy nanostructure.

**Electrical conductivity analysis**

The electrical conductivity of pure PPy and YSZ/PPy nanocomposite was determined using four point probe set–up and Keithley digital multimeter. The temperature dependent electrical conductivity of YSZ/PPy nanocomposites and electrical conductivity as a function of YSZ wt.% loading is presented in Figure 5 (a, b). The electrical conductivity of pristine PPy was found to be 9.9 cm$^{-1}$ at 28°C$^{16}$. However, YSZ/PPy composite shows a higher value of conductivity. The electrical conductivity of the composite was found to be increased abruptly with increasing YSZ loading. The maximum value of electrical conductivity was observed at 50 wt.% of YSZ loading Figure 5(b). It was also observed that the conductivity of YSZ/PPy composite materials increased with the rise in temperature which shows it’s semiconductor behavior.

Above 200°C, the YSZ/PPy composite material was decomposed easily and the conductivity of materials decreased rapidly. Therefore conductivity measurements were carried out up to 200°C Figure 5(a). The highly increase in the electrical conductivity of the YSZ/PPy composite is mainly associated with the presence of YSZ. The YSZ lead to boost the the electrical network to higher level. This large enhancement of electrical conductivity is observed due to the formation of a highly electrically conductive network in composites because of the strong YSZ/PPy interactions promote transfer of charge carriers across the interface of the composites. Therefore highest conductivity was observed for 50 wt.% of YSZ loading. Hence YSZ/PPy composite with 50 wt.% of loading was used for further characterization and applied for supercapacitor material.
**Supercapacitive studies**

Pure YSZ and YSZ/PPy electrodes were used in electrochemical supercapacitors. Supercapacitive performance was tested by means of cyclic voltammetry, galvanostatic charge–discharge and electrical impedance spectroscopy techniques.

**Cyclic voltammetry analysis**

Figure 6(a) shows the redox peaks of YSZ/PPy electrode within the potential window from -0.8 to +0.4 V versus SCE with variable scan rates (10, 20, 30, 50, 100 mVs⁻¹). The YSZ/PPy showed different CV peaks as compared to pure PPy electrodes. The oxidation peaks are observed at +0.02V versus SCE corresponds to oxidation of YSZ/PPy chain. In the reverse scan the reduction peak is observed at -0.31V versus SCE corresponds to reduction of YSZ/PPy chain. This CV is generally rectangular in shape. The oxidation reduction peaks are observed in both. This redox peaks are responsible for pseudocapacitive behaviour. The inter-facial and specific capacitance decrease with increasing scan rate. The inner active sites cannot sustain the redox transitions completely due to the diffusion effect of protons within the electrode. It is observed that all redox peaks indicate that the current–potential behavior is voltage dependent. The redox reaction of PPy chain with electrolyte is responsible for supercapacitive performance.

**Stability of YSZ/PPy electrode**

The electrochemical stability of YSZ/PPy electrode in 1M H₂SO₄ was tested by cyclic voltammetry method. Figure 6(b) shows the typical C-V curves for 1st and 1000th cycles. Retention of 98% was obtained after 1000 cycles. The long-lasting stability and the repeatability of electrode material are considered for the selection of its supercapacitor applications. There is no significant decrease in specific capacitance is observed during 1st cycle to 1000th cycle which indicates the excellent electrochemical stability of YSZ/PPy electrode over a large number of cycle operations in energy storage application. The specific and inter-facial capacitance are found to decrease in small amount up to 1000th cycle because of the small loss of active material.

**Galvanostatic charge–discharge (GCD) study**

Galvanostatic charge–discharge study of YSZ and YSZ/PPy electrode are carried out at different current density. The characteristic charge–discharge curves of electrodes in 1M H₂SO₄ electrolyte at -0.4 to +0.8 V/SCE is shown in Figure 6(c,d) It is observed that, almost all discharging curves of YSZ electrode exhibit ideal linear curve, which point out the pseudocapacitive behavior. But in case of YSZ/PPy electrode, discharging curves are not perfect straight lines. Therefore, the process of a Faradaic reaction occurs. Hence, it shows supercapacitive property. Internal resistance is most important and it is responsible for the initial potential drop. The internal resistance which depends on the surface morphology of electrode is due to the presence of inter-facial contact resistance between electrodes and 1M H₂SO₄ electrolyte. Due to the YSZ loading, the interaction between YSZ and PPy in the polymer matrix is responsible for the significant change in morphology of composite. However, the resistance of supercapacitor is decreased because of the generation of a large electrode/electrolyte interface due to various morphologies of above electrode materials. The discharging time of electrodes increase in the order of YSZ < YSZ/PPy. This feature may be attributed to the enhanced conductivity of YSZ/PPy electrodes, which facilitates the fast charge transport in the YSZ/PPy composite electrode. The supercapacitive parameters such as specific capacitance (Cₛ), specific energy (Eₛ), specific power (Pₛ) and coulombic efficiency (η%) for PPy, YSZ and YSZ/PPy electrodes were estimated from the discharge process according to the following equation:

\[
Specific\ capacitance(C_s) = \frac{(I_d * T_d)}{\Delta V} * W
\]  
\[
Specific\ energy(E_s) = \frac{(C_s * \Delta V^2)}{2}
\]  
\[
Specific\ power(P_s) = \frac{E_s^2}{T_d}
\]  
\[
Coulombic\ efficiency(\eta\%) = \frac{(T_d/T_s) * 100}
\]

Where I_d is the discharge current, T_d is the discharge time; V is the potential change during discharge process (potential window) and W is the mass of active material. The variation of specific capacitance, specific energy, specific power and coulombic efficiency obtained for electrodes at 1 Ag⁻¹ are shown in Table II. The cycling stability of the YSZ and YSZ/PPy electrodes are presented in Figure 6(e). For the YSZ electrode, there is a slowly decrease in capacitance by roughly 2.3% upto 200 cycles and then remains constant up to 1000 cycles. But 0.7% capacitance decrease is observed for the YSZ/PPy electrode, demonstrating that the composite has preferable electrochemical cycling stability over YSZ. Figure 6(f) comparing the specific capacitance calculated from the charge discharge curves, YSZ/PPy electrode was found to be exhibits a value higher than that of YSZ at each scan rate, verifying the promoted electrochemical activity due to better charge rate performance. At 1 Ag⁻¹, the specific capacitance of YSZ/PPy reaches 640 Fg⁻¹. The specific capacitance decrease gradually for both the YSZ and YSZ/PPy materials, with increasing in scan rate. This is credited to the inadequate response of the electrodes on the grounds.
that the electrolyte can scarcely go into the inside of the particles to utilize the internal surface region at the higher scan rate. In case of pure PPy, the specific capacitance (624 F g\(^{-1}\)) for the scan rate of 1.0 A/g was reported in earlier work\(^{16}\). The specific capacitance calculated from the discharge curves of pure YSZ electrode are 430, 360, 240, 160, 90, 50 and 24 F g\(^{-1}\) for the scan rate of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 A/g, respectively. As comparable of YSZ electrode, the specific capacitance of YSZ/PPy electrode are found to 640, 510, 340, 260, 260, 160 and 130 F g\(^{-1}\) for their respective scan rates. Further, specific capacitance, specific energy, specific power and coulombic efficiency of YSZ/PPy electrode found to be greater as compared to PPy and YSZ electrode. Therefore, it is confirmed that the YSZ/PPy electrode found to be more efficient supercapacitive performance than pure YSZ electrode.

**Electrochemical impedance spectroscopy**

The electrochemical impedance measurement were carried out between the frequency range from 40 Hz to 20 MHz using 10 mV of sinusoidal signal. The Nyquist plots and its relevant equivalent circuit are shown in Figure 7. The complex mechanism of charge storage and electrolyte diffusion in YSZ/PPy electrode is determined using electrochemical impedance spectroscopy (EIS). The half-circle of EIS shows that the terminal procedure is constrained by the electrochemical response at high frequencies and by the mass exchange at low frequencies. YSZ/PPy shows large amount of charge transfer resistance (R\(_{ct}\) = 32.29 ohm) in the semicircle high frequency region. The highest peak of semicircle is present in high frequency region and vertical line was not found to be observed in the low frequency region. The intersection of semicircle on the real axis elucidate the solution resistance (R\(_{s}\) = 7.61 ohm) of electrolyte. The lower value of R\(_{s}\) represent the high transportation of H\(^+\) ions through the interface of electrode and highly conductive electrolyte. The YSZ/PPy exhibits very small value of R\(_{ct}\) which is attributed to very small electrode polarization and more effective redox reaction. Hence, the performance of electrode material is high.

**Conclusions**

The inter-facial interactions between YSZ and PPy in the nanocomposite was interpreted by FT–IR studies. X–ray diffraction pattern of YSZ/PPy nanocomposite showed the highly intense broad base peaks indicating the nano crystallinity of the composite. The temperature dependent conductivity of YSZ/PPy material enhanced with the rise in temperature which shows the semiconductor behaviour. The different weight % of YSZ into the PPy matrix lead to boost the connectivity of electrical network. Therefore, higher electrical conductivity of nanocomposites is observed at 50 wt. % loading of YSZ as compared to PPy. The specific capacitance (640 F g\(^{-1}\)), specific energy (12.8 Wh Kg\(^{-1}\)), specific power (51 kW Kg\(^{-1}\)) and coulombic efficiency (98%) of YSZ/PPy electrode are found to be enhanced as compared to pure YSZ. Therefore, it is concluded that the YSZ/PPy electrode is emerged as high performance supercapacitor.

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**Table 1.** Composition and labeling of composite materials

| Designation | YSZ(%) | YSZ/PPy (%/%) | dense layer | PPy (%) | floating layer |
|-------------|--------|--------------|-------------|---------|----------------|
| PPy         | 00     | 00           |             | 100     |                |
| YSZ/PPy-1   | 10     | 10/20        |             | 80      |                |
| YSZ/PPy-2   | 20     | 20/40        |             | 60      |                |
| YSZ/PPy-3   | 30     | 30/60        |             | 40      |                |
| YSZ/PPy-4   | 40     | 40/80        |             | 20      |                |
| YSZ/PPy-5   | 50     | 50/100       |             | 00      |                |
| YSZ/PPy-6   | 60     | (50/100)+10%YSZ |             | 00      |                |
| YSZ/PPy-7   | 70     | (50/100)+20%YSZ |             | 00      |                |

**Table 2.** Specific capacitance, specific energy, specific power and columbic efficiency for electrodes at constant current density of 1 Ag$^{-1}$

| Electrodes | Specific capacitance (F g$^{-1}$) | Specific energy (Wh Kg$^{-1}$) | Specific power (kW Kg$^{-1}$) | Columbic efficiency(η%) |
|------------|----------------------------------|-------------------------------|-------------------------------|--------------------------|
| YSZ        | 430                              | 8.6                           | 34                            | 94.2                     |
| YSZ/PPy    | 640                              | 12.8                          | 51                            | 98                       |
Figure 1. Schematic representation of Synthesis of YSZ and YSZ/PPy composite material.

Reaction:

\[ [\text{Zr} \ (\text{NO}_3)_4] + \text{C}_6\text{H}_8\text{O}_7 + [\text{Y} \ (\text{NO}_3)_{3.6}\text{H}_2\text{O}] \]

Steps:
- Hydrothermal: 200 °C
- Centrifuge: Wash and dry
- Decant PPy layer: Wash & dry @60°C
- Oxidation
- SDS
- Pyrrole

Results:
- YSZ/PPy composite
Figure 2. FT–IR spectrum of YSZ, PPy and YSZ/PPy composites.
Figure 3. SEM image of YSZ (a,b), PPy (c,b), YSZ/PPy (e,f) and EDS (g)
Figure 4. XRD pattern of PPy (inset), YSZ and YSZ/PPy composite.

Figure 5. Temperature dependent conductivity of PPy and YSZ/PPy (a), electrical conductivity as a function of different wt % loading of YSZ (b).
Figure 6. (a) Cyclic voltammograms for YSZ/PPy electrode at different scan rates in 1 M aqueous H$_2$SO$_4$ electrolyte. (b) Cyclic voltammograms for stability of YSZ/PPy electrode at 1$^{st}$ and 1000$^{th}$ cycles. (c) Galvanostatic charging/discharging curves of YSZ measured with different scan rates. (d) Galvanostatic charging/discharging curves of YSZ/PPy measured with different scan rates. (e) Comparison of specific capacitance values between YSZ and YSZ/PPy at different cycle number. (f) Comparison of specific capacitance values between YSZ and YSZ/PPy at different scan rates.
Figure 7. Nyquist plot and its equivalent circuit of YSZ/PPy electrode.
Figure 8. Graphical abstract