SnO₂–Au hybrid nanoparticles as effective catalysts for oxygen electroreduction in alkaline media

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ABSTRACT

SnO₂ nanoparticles were synthesized by a facile electrochemical method based on anodic oxidation of a tin metal sheet. The resulting particles, with an average diameter of about 20 nm, were then loaded with varied amounts of HAuCl₄, forming SnO₂–Au(x) (x = 0, 0.095, 0.38, 0.76, 1.9, 3.0, and 3.8 at.%) hybrid nanoparticles after calcination at elevated temperatures (700 °C). X-ray diffraction (XRD) and transmission electron microscopic (TEM) measurements showed that the SnO₂ particles exhibited high crystallinity with a rutile structure, and spherical Au nanoparticles were dispersed on the surface of the SnO₂ support. Based on the TEM images and the width of the Au(2 0 0) XRD diffraction peak, the size of the Au nanoparticles was found to be between 15 and 35 nm in diameter and decrease with increasing loading of the original HAuCl₄ precursor. The electrocatalytic activity of the resulting SnO₂–Au(x) composite nanoparticles toward oxygen reduction reaction (ORR) was then evaluated by cyclic and rotating disk voltammetric measurements in alkaline solutions. It was found that the incorporation of gold nanoparticles led to apparent improvement of the catalytic activity of SnO₂ nanoparticles. Moreover, the ORR electrocatalytic activity exhibited a strong dependence on the gold loading in the hybrid nanoparticles, and the most active catalyst was found with a gold loading of 1.9 at.%, based on the reduction current density and onset potential of ORR. Furthermore, at this gold loading, oxygen reduction was found to follow the efficient four-electron reaction pathway, whereas at other Au loadings, the number of electron transfer involved in oxygen reduction varied between 1 and 3. Additionally, Tafel analysis suggested that at low overpotentials, the first electron transfer might be the limiting step in oxygen reduction, whereas at high potentials, oxygen adsorption appeared to play the determining role at the SnO₂–Au hybrid electrodes. These results indicate that the SnO₂–Au composite nanoparticles might serve as effective catalysts for oxygen electroreduction in alkaline media.

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1. Introduction

Direct liquid fuel cells have been attracting much attention as potentially green, inexpensive, and efficient power sources for a variety of practical applications, such as electrical vehicles, portable as well as stationary electronic devices, etc. [1,2]. A typical fuel cell is composed of two electrodes, anode for the oxidation of fuel molecules (hydrogen, methanol, formic acid, etc.) and cathode where the reduction of oxygen occurs. Yet, despite substantial improvements of fuel cell performance in recent years, the widespread commercialization of fuel cells has been impeded by several challenging obstacles. Of these, one major issue is related to the cathodic reactions which exhibit significant overpotentials because of the sluggish reaction kinetics. At present, among the metal catalysts used, platinum and platinum-based alloys generally show the highest catalytic activity for both anode and cathode reactions [3–8]. However, platinum is costly and of limited reserve. Therefore, recently extensive research efforts have also been devoted to the development of non-Pt electrocatalysts for fuel cell electrochemistry, including transition metal oxides [9,10], transition metal sulfides [11], transition metal macrocyclic complexes [12,13], and metal-containing porphyrin systems [14].

Of these Pt-free electrocatalysts, transition metal oxides are attracting much attention as a kind of efficient electrode catalysts for oxygen reduction reactions (ORR) because of their long-term chemical stability, high photocatalytic activity, and low-cost synthesis. For instance, titanium dioxides are widely used for ORR in both acidic and alkaline media, with a high overpotential [15–19]. Mentus [10] studied ORR on anodically formed TiO₂ in both alkaline and acidic solutions and found that the reactions followed the direct 4e⁻ reduction pathway in alkaline media, whereas in acidic media, the inefficient 2e⁻ reduction pathway was favored.

Similarly, tin oxides have also been evaluated as potential cathode catalysts for fuel cell reactions, although the study is relatively scarce. For instance, Liu et al. recently observed that titanium oxide...
and tin oxide films made by sputtering methods displayed rather comparable activity for oxygen reduction [9]. Furthermore, tin oxide supported Au and Pt nanoparticles have also been found to act as effective catalysts for oxygen reduction [20–23].

In the present study, we examine the electrocatalytic activity of a series of SnO2–Au hybrid nanoparticles in the electroreduction of oxygen. The SnO2 nanoparticles were first synthesized in a single step by electrochemical oxidation of a tin metal sheet in a non-aqueous electrolyte. Then a controlled amount of HAuCl4 was loaded onto the SnO2 nanoparticles. Calcination at elevated temperatures led to the formation of Au nanoparticles that were dispersed onto the SnO2 surfaces. The structures of the SnO2–Au hybrid nanoparticles were characterized by X-ray diffraction (XRD) and transmission electron microscopy (TEM) measurements. The electrocatalytic activities of these functional nanocomposites for oxygen reduction were then investigated by cyclic voltammetry and rotating disk voltammetry in alkaline solutions.

2. Experimental

2.1. Materials

Tin foil (0.25 mm thick, 99.8% purity (metal basis)) and ethylene glycol (99+% w/w) were purchased from Aldrich. Ammonium fluoride (NH4F, 98%, extra pure), potassium perchlorate (KClO4, 98%), and sodium hydroxide (NaOH, 86%) were purchased from ACROS. Hydrogen tetrachloroauric acid (HAuCl4) was synthesized by dissolving ultra-high purity gold (99.999%, Johnson Matthey) in freshly prepared aqua regia. Water was supplied by a Barnstead Nanopure water system (18.3 MΩ cm). Ultrapure N2 and O2 were used for purging the electrolyte solutions and nitrogen electrochemical reactions, respectively. All other chemicals were purchased from typical commercial sources and used without further treatment.

2.2. Sample preparation

SnO2 nanoparticles were prepared by using a two-electrode cell in which the tin foil was used as the sacrificial anode and a Pt coil as the cathode, along with a non-aqueous electrolyte consisting of NH4F in ethylene glycol [24]. Before the experiments, the tin sheet was decreased by sonication in acetone, ethanol, and Nanopure water successively and then dried at room temperature, affording purified SnO2 nanoparticles.

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0.4 mg of the prepared SnO2 nanoparticles was then added into 10 mL of an aqueous solution of HAuCl4 at different concentrations (varying from 0.25, 1, 2, 5, 8, to 10 mM), and the mixture was under vigorous stirring overnight. The Au-loaded tin oxide powders were then centrifuged and thoroughly washed with Nanopure water. The Au-loaded tin oxide powders were dispersed onto the SnO2 surfaces. The structures of the SnO2–Au hybrid nanoparticles were characterized by X-ray diffraction (XRD) and transmission electron microscopy (TEM) measurements. The electrocatalytic activities of these functional nanocomposites for oxygen reduction were then investigated by cyclic voltammetry and rotating disk voltammetry in alkaline solutions.

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2.3. Electrochemistry

A glassy carbon (GC) disk electrode (Bioanalytical Systems, diameter 3.0 mm) was first polished with alumina slurries (0.05 μm) and then cleaned by sonication in 0.1 M HNO3, 0.1 M H2SO4, and Nanopure water for 10 min successively. The SnO2–Au(x) hybrid particles prepared above were then deposited onto the cleaned GC electrode surface by adopting a literature procedure [24]. Briefly, 1 mg of the particles was dispersed ultrasonically in a mixture of 700 μL of pure water and 60 μL of 5 wt.% Nafion solution. After the formation of a homogenous ink, 8 μL of the catalyst ink was dropcast onto the GC electrode surface with a micropipette and then dried in air. The electrodes were denoted as SnO2–Au(x)/GC.

All electrochemical experiments were performed using a standard three-electrode configuration. A Ag/AgCl (in 3 M NaCl, aq) (Bioanalytical Systems, MF-2052) and a Pt coil were used as the reference and counter electrodes, respectively. All electrocatalytic reactions were examined by first bubbling the electrolyte solution with ultra-high purity oxygen for at least 15 min and then blanketing the solution with an oxygen atmosphere during the entire experimental procedure. All electrochemical experiments were carried out at room temperature.

2.4. XRD and TEM characterizations

Powder X-ray diffraction (XRD) measurements were performed with a Rigaku Mini-flex Powder Diffractometer using Cu Kα radiation with a Ni filter (λ = 0.154059 nm at 30 kV and 15 mA) which features a detection limit of 0.04°. The particle size and morphology of the Au-doped SnO2 particles were examined with a JEOL 1200 EX transmission electron microscope (TEM) at 80 kV. The samples were prepared by casting a drop of the particle solution (1 mg mL⁻¹) in ethanol onto a 200-mesh carbon-coated copper grid.

3. Results and discussion

3.1. Structural characterizations

To examine the crystallinity of the SnO2–Au(x) hybrid particles, powder X-ray diffraction measurements were first carried out. Fig. 1(A) shows the XRD patterns of the SnO2 nanoparticles decorated with various amounts of Au (x = 0, 0.095, 0.38, 0.76, 1.9, 3.0, and 3.8 at.%, corresponding to curves (b)–(h), respectively) after thermal calcination at 700 °C. The JCPDS data of SnO2 (cassiterite, No. 41-1445) are also included in the figure as curve (a). It can be seen that all the samples show clear, sharp, and strong diffraction peaks that are in excellent agreement with the tetragonal structure (rutile type) of SnO2 (curve a), with the lattice constants of a = 4.738 Å and c = 3.187 Å. The observed XRD patterns strongly indicate that the heat-treated particles exhibit high crystallinity (indeed high-resolution TEM studies show very well-defined crystalline lattices [24]). Additionally, no diffraction peaks from impurities such as unreacted tin and tin oxides of other crystalline phases are observed, suggesting the purity of the rutile SnO2 structures. Furthermore, the average size of the SnO2 nanoparticles may be estimated by the Debye–Scherrer equation, D = Kλ/βcosθ, where D is the diameter of the nanoparticles, K = 0.9, λ(Cu Kα) = 1.54059 Å, and β is the full width at half maximum (FWHM) of the diffraction peaks. Based on the SnO2 (1 1 0) and (1 1 1) diffraction peaks, the average size of the SnO2 particles was estimated to be 20 nm.

The diffraction patterns of gold nanoparticles were found at 2θ between 40 and 50° (dashed box in panel A, which is magnified in panel B). It can be seen that with increasing gold loading, the diffraction peaks at ca. 44.5°, which are ascribed to the Au(2 0 0) crystalline
were magnified in panel (B) to display the diffraction peak from Au particles (at \( g \) 3.0 at.\%, and (h) 3.8 at.\%). All the SnO\(_2\) particles were synthesized at 30 V and calcined in air at 700\( ^\circ \)C. The XRD patterns with 2\( \theta \) in the range of 40–50\( ^\circ \) (dashed box) were magnified in panel (B) to display the diffraction peak from Au particles (at 44.5\( ^\circ \)).

Fig. 1. (A) XRD patterns of (a) bulk SnO\(_2\) from the Joint Committee Powder Diffraction Standard (JCPDS) No. 41-1445; (b) pure SnO\(_2\) nanoparticles and SnO\(_2\) particles loaded with different Au contents: (c) 0.095 at.\%, (d) 0.38 at.\%, (e) 0.76 at.\%, (f) 1.9 at.\%, (g) 3.0 at.\%, and (h) 3.8 at.\%. All the SnO\(_2\) particles were synthesized at 30 V and calcined in air at 700\( ^\circ \)C. The XRD patterns with 2\( \theta \) in the range of 40–50\( ^\circ \) (dashed box) were magnified in panel (B) to display the diffraction peak from Au particles (at 44.5\( ^\circ \)).

The hybrid nanoparticles were further analyzed by TEM measurements. Fig. 2 shows the representative TEM micrographs of SnO\(_2\)–Au nanoparticles loaded with different Au contents. It can be seen that after calcination at 700\( ^\circ \)C, Au nanoparticles appeared to form large agglomerates on the surface of the SnO\(_2\) support. Yet, based on the small number of nanoparticles that were recognizable outside of these aggregates (highlighted by red circles in Fig. 2), one can see that the Au nanoparticles exhibit mostly spherical shape, and the core diameter decreases with increasing Au loading in the nanocomposites, similar to the trend observed in XRD measurements (Table 1). For instance, at \( x = 0.095 \) at.\%, the diameter of the gold particles is about 29.3 nm whereas at \( x = 3.8 \) at.\%, it decreases drastically to 15.2 nm. This may be accounted for by the growth mechanism of gold nanoparticles. At higher Au salt concentrations, more Au nuclei would be formed in a short period of time, leading to the suppression of the growth of Au nanoparticles and hence smaller particles as the final products.

From Table 1, one might note that the particle core sizes obtained from XRD measurements are somewhat larger than those evaluated from TEM measurements. This discrepancy may be, at least partly, ascribed to the relatively weak Au(2 0 0) diffraction peaks in XRD patterns, which renders it difficult to have an accurate assessment of the peak width, in particular, at low Au loadings.

3.2. Cyclic voltammetry

The electrocatalytic activity of the SnO\(_2\)–Au(x)/GC electrodes for oxygen reduction was then evaluated by cyclic voltammetry in alkaline solutions. Fig. 3 shows representative cyclic voltammograms of the SnO\(_2\)–Au(0.095 at.\%)/GC electrode in an aqueous electrolyte of 0.02 M NaOH + 0.2 M KClO\(_4\) (pH 12.2) that was saturated either with N\(_2\) or O\(_2\) within the potential range of +0.6 to −0.7 V. It can be seen that when the electrolyte solution was saturated with N\(_2\) the voltammetric response was essentially featureless (dashed curve). In contrast, in the O\(_2\)-saturated solution, the cathodic current increased significantly (solid curve), with a well-defined peak at ca. −0.45 V, indicative of apparent electrocatalytic activity of the nanocomposite for oxygen reduction. The figure inset shows the cathodic peak current (\( I_p \)) as a function of the square root of potential sweep rate. The linearity of the plot is consistent with the typical feature of diffusion-controlled oxygen reduction reactions. Similar behaviors were also observed with other SnO\(_2\)–Au(x)/GC electrodes.

Fig. 4 shows the voltammograms for oxygen reduction at the SnO\(_2\)–Au(x)/GC electrodes with different Au loading (\( x \) ranging from 0 to 3.8 at.\%). On the basis of cathodic current density and onset potential for oxygen reduction, at least two conclusions can be drawn: (1) the catalytic activity for ORR is improved with the SnO\(_2\)–Au hybrid nanoparticles in comparison to the

Table 1

<table>
<thead>
<tr>
<th>Au loading (x, at%)</th>
<th>0</th>
<th>0.095</th>
<th>0.38</th>
<th>0.76</th>
<th>1.9</th>
<th>3.0</th>
<th>3.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size evaluated from XRD (nm)(^a)</td>
<td>20</td>
<td>34.5</td>
<td>33.0</td>
<td>30.4</td>
<td>27.2</td>
<td>20.4</td>
<td>18.0</td>
</tr>
<tr>
<td>Particle size evaluated from TEM (nm)(^b)</td>
<td>29.3</td>
<td>27.5</td>
<td>27.3</td>
<td>25.3</td>
<td>23.5</td>
<td>17.7</td>
<td>15.2</td>
</tr>
<tr>
<td>Number of electron transferred ( (n/\ell) )</td>
<td>1.0</td>
<td>1.3</td>
<td>1.8</td>
<td>2.6</td>
<td>4.1</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Onset potential [V](^c)</td>
<td>−0.24</td>
<td>−0.21</td>
<td>−0.23</td>
<td>−0.11</td>
<td>+0.06</td>
<td>−0.12</td>
<td>−0.11</td>
</tr>
<tr>
<td>Current density at −0.3 V [mA cm(^{-2})](^d)</td>
<td>−0.06</td>
<td>−0.08</td>
<td>−0.08</td>
<td>−0.16</td>
<td>−0.41</td>
<td>−0.24</td>
<td>−0.15</td>
</tr>
<tr>
<td>Tafel slopes (mV/dec)(^e)</td>
<td>−119.5</td>
<td>−147.4</td>
<td>−161.4</td>
<td>−230.2</td>
<td>−259.6</td>
<td>−201.2</td>
<td>−239.4</td>
</tr>
<tr>
<td></td>
<td>−330.6</td>
<td>−2028.6</td>
<td>−332.6</td>
<td>−570.2</td>
<td>−653.9</td>
<td>−434.6</td>
<td>−423.8</td>
</tr>
</tbody>
</table>

\(^a\) The average size was evaluated from the Au(2 0 0) diffraction peak of the XRD patterns as shown in Fig. 1(B).

\(^b\) The average size was evaluated from the TEM images as shown in Fig. 2.

\(^c\) The numbers of electron transferred for ORR were calculated from Eqs. (1) and (2) by curve fitting of the Koutecky–Levich plots (Fig. 5(B)).

\(^d\) Onset potential and current density at −0.3 V were obtained from the rotating disk voltammograms at the rotation rate of 225 rpm (Fig. 6(A)).

\(^e\) The Tafel slopes at the low and high current density regions were listed at the top and bottom, respectively (Fig. 6(B)).
SnO₂ nanoparticles alone (i.e., x = 0) and (ii) the SnO₂–Au(1.9 at.%) sample appears to exhibit the best catalytic performance within the series. For instance, the cathodic peak current density at the SnO₂/GC electrode is −0.57 mA cm⁻², whereas it increases rather markedly to −2.19 mA cm⁻² at the SnO₂–Au(1.9 at.%) GC electrode. Additionally, the onset potential for oxygen reduction at the SnO₂–Au(1.9 at.%) GC electrode (+0.06 V) is substantially more positive than that at the SnO₂/GC electrode (−0.24 V). Such enhancement of the electrocatalytic activity has also been observed with other metal oxide materials loaded with precious or non-precious metal nanoparticles [20,23,25,26].

Bulk gold is usually considered to be a poor electrocatalyst for oxygen reduction (for instance, as manifested by the dashed curve in Fig. 4), because of the low affinity to oxygen adsorption and the difficulty of donating electrons to O₂ to form O₂⁻. However, at the SnO₂–Au hybrid nanoparticles, according to the bifunctional mechanism proposed by Baker et al. [21], chemisorption of O₂ onto the SnO₂ surface as O₂⁻ may be facilitated by Sn²⁺ ions produced by cathode polarization. Further reduction of O₂⁻ to H₂O may then be catalyzed by Au nanoparticles.

3.3. Rotating disk voltammetry

The dynamics of oxygen reduction by the SnO₂–Au hybrid nanocatalysts were then examined as a function of the catalyst composition by rotating disk voltammetry. Fig. 5 shows a series of rotating disk voltammograms of oxygen reduction at two SnO₂–Au/GC electrodes, x = 0.095 at.% (A) and 1.9 at.% (B), at different rotation rates in an aqueous solution of 0.02 M NaOH + 0.2 M KClO₄ (pH 12.2) saturated with O₂. Note that the background current acquired with a nitrogen-saturated solution has been subtracted from the voltammetric currents at the respective electrode.
It can be seen that the limiting current density increases with increasing rotation rate. Again, similar voltammetric features were also observed with other SnO2–Au(x)/GC electrodes, suggesting the apparent activity of the hybrid nanoparticles towards oxygen reduction.

For oxygen reduction on a rotating disk electrode (RDE), the current density can be described by the Koutecky–Levich equation:

$$\frac{1}{J} = \frac{1}{J_K} + \frac{1}{J_L} = \frac{1}{J_K} + \frac{1}{B\omega^{1/2}}$$

(1)

$$B = 0.62nFC_OD_O^{2/3}v^{-1/6}$$

(2)

$$J_K = nFkC_O$$

(3)

where \(J\) is the measured current density, \(J_K\) and \(J_L\) are the kinetic and diffusion limiting current density, respectively, \(\omega\) is the electrode rotation rate, \(n\) is the overall number of electron transfer, \(F\) is the Faraday constant, \(C_O\) is the bulk concentration of O2 dissolved in the electrolyte, \(D_O\) is the O2 diffusion coefficient, and \(v\) is the kinematic viscosity of the electrolyte. Therefore, based on the Koutecky–Levich equation, a plot of the inverse of the current density \((J^{-1})\) versus \(\omega^{-1/2}\) should yield a straight line with the intercept corresponding to \(J_K\) and the slopes reflecting the so-called \(B\) factor (Eq. (2)). The number of electron transfer in the O2 reduction process can then be calculated from the \(B\) factor by using the literature data\[27,28\] of \(C_O = 2.5 \times 10^{-6} \text{ M}, D_O = 1.9 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) and \(v = 9.97 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\). The figure insets depict the corresponding Koutecky–Levich plots for these two SnO2–Au/GC electrodes. It can be seen that at both electrodes the slopes remain approximately constant over the potential range under study (−0.30 V to −0.50 V), indicating a consistent number of electron transfer for ORR at different electrode potentials. Specifically, based on Eqs. (1) and (2), the number of electron transfer in oxygen reduction \((n)\) was estimated to be 1.3 for \(x = 0.095\) at.%, suggesting incomplete reduction of oxygen at this electrode, whereas at \(x = 1.9\) at.%, \(n = 4.1\), indicative of efficient reduction of oxygen into water. The estimation of \(n\) for other electrodes was also carried out in a similar manner and the results are summarized in Table 1. It can be seen that for pure SnO2, \(n = 1.0\), indicative of poor electrocatalytic activity of SnO2 alone for oxygen reduction. However, upon the loading of Au nanoparticles onto the oxide support, the value of \(n\) increases: 1.3 (\(x = 0.095\) at.%), 1.8 (0.38 at.%), 2.6 (0.76 at.%), 4.1 (1.9 at.%), 3.2 (3.0 at.%), and 3.0
seen that the SnO2–Au/GC electrode at Koutecky–Levich plots of the respective electrode. First, it can be observed among the series of samples, exhibiting the highest kinetic current density at +0.06 V, whereas at other gold loadings a more negative onset potential was observed in voltammetric measurements (Fig. 4). For instance, at +0.06 V, the electrode at x = 1.9 at.% exhibited the largest slopes in each current density region, implying that oxygen adsorption might play a significant role in the electroreduction process at this electrode.

It should be noted that in general the electrocatalytic activity of large gold nanoparticles (and bulk gold) for oxygen reduction is very weak. For instance, in a recent study [31], incomplete reduction of oxygen (n ≈ 2) was observed with Au nanoparticles larger than 2 nm in diameter. Yet, in the present study, despite the very large gold particle size (15–35 nm), the SnO2–Au hybrid nanoparticles appeared to be fairly efficient in the electrocatalytic reduction of oxygen (n = 3 to 4) at x ≥ 1.9 at.%. This suggests that the hybridization of Au nanoparticles with SnO2 nanomaterials may be an effective route to the enhancement of the electrocatalytic activity as compared to Au or SnO2 alone, as a consequence of the metal–support interactions [21,32,33].

Comparison with other metal nanoparticle–metal oxide nanocomposite electrocatalysts also shows that the SnO2–Au(x%) hybrid nanoparticles exhibit promising catalytic activity. For example, on titanium oxide electrodes [10,16], the onset potential of ORR was found to be around −1.0 V, which is far more negative than those observed with the SnO2–Au(x%) catalysts (−0.24 V to +0.06 V for x = 0 to 3.8 at.%). This suggests that the hybridization of Au nanoparticles with SnO2 nanomaterials may be an effective route to the enhancement of the electrocatalytic activity as compared to Au or SnO2 alone, as a consequence of the metal–support interactions [21,32,33].

In this study, SnO2–Au hybrid nanoparticles were synthesized and examined as novel electrocatalysts toward oxygen reduction reactions. XRD measurement showed that after calcination at 700 °C the SnO2 particles exhibited a tetragonal rutile structure with an average size of about 20 nm. TEM images revealed that the SnO2 nanoparticles were highly crystalline and the Au nanoparticles were dispersed on the SnO2 surface with the average core diameter varied from 15 to 35 nm. The catalytic activity of the SnO2–Au hybrid nanoparticles for ORR was then studied and compared by cyclic voltammetry and rotating disk voltammetry. The results showed that the electrocatalytic activity of the SnO2–Au...
nanocomposites was markedly enhanced as compared to that of the SnO$_2$ nanoparticles alone, and the activity varied sensitively with the loading of the Au content. Importantly, within the present experimental context, the SnO$_2$–Au(1.9 at.%) sample exhibited the best electrocatalytic activity with the highest reduction density and the most positive onset potential, where oxygen reduction followed an efficient four-electron reaction pathway. Additionally, Tafel analysis showed that at low overpotentials, the first electron transfer might be the limiting step in oxygen reduction, whereas at high potentials, oxygen adsorption appeared to play the determining role at the SnO$_2$–Au hybrid electrodes. The present study suggests that SnO$_2$–Au nanocomposite particles may serve as effective non-platinum electrocatalysts in fuel cell reactions in alkaline media.

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