The lack of stable and economic supporting materials at high voltages hampers the development of electrocatalysts for oxygen evolution reaction (OER), which is the major source of energy loss in water splitting to produce hydrogen. In this work, we developed systematic methods to evaluate candidate compounds that can potentially replace traditional carbon support for OER catalysts. Stability, economic and conductivity criteria of the oxide support materials were studied and discussed. A nano-sized antimony-doped tin oxide was fabricated to support RuO₂, which was shown to provide the highest stability and activity of OER in 0.5 M H₂SO₄ up to 2.5 V vs RHE and up to 55 °C.

In this work, we systematically studied a number of commercial and synthesized oxide materials as OER catalyst supports, where their conductivity, electrochemical stability, and activity improvement effect to OER catalysts were compared. Among all the commercial materials screened, antimony-doped tin oxide (ATO) showed a reasonable cost, a high conductivity, and a high stability, which makes it the most promising candidate for the next-generation support materials. In addition, we synthesized nano-sized ATO particles using a sol-gel method, which showed smaller particle size, higher conductivity, and greater improvement to electrochemical surface area compared with the commercial ATO when supporting RuO₂ to catalyze OER in acid electrolytes. The OER activity and stability of RuO₂ NPs supported by the sol-gel synthesized ATO surpassed those supported by the commercial ATO, the high-surface-area carbon, or the other support materials in previous studies.

**Experimental Methods and Materials**

**Materials selection.—** To find support materials that could replace carbon, we looked for materials that are stable at pH 0 and above 2.0 V vs RHE. A common tool to predict the stability of the materials is a formalism of candidate support materials in acid electrolyte under the OER operational condition. In addition, there lacks a deep investigation of the formal criteria for support material selection covering the cost, conductivity, stability, and other characters of the candidate materials, which is highly desirable in order to facilitate the development of long-lived catalyst supports used in acidic conditions such as those in PEM electrolyzers.

Developing new electrochemical energy storage and conversion devices with higher energy efficiency and energy density is important for the application of sustainable new energy sources. However, the slow kinetics of oxygen evolution reaction (OER) causes great energy loss in many electrochemical devices, including water splitting electrolyzers and rechargeable metal-air batteries. To overcome the slow kinetics of OER and improve the efficiency of energy storage devices, precious-metal oxide catalysts such as RuO₂ and IrO₂ have been widely used in both acid and basic solutions, which suffer from high cost and low elemental abundance. Recently, various non-precious-metal oxides have been developed as the next-generation OER catalysts with high and stable OER activity in basic electrolytes, however they are not stable in acid solutions. Currently, the acidic electrolyte is still widely used in the industrial applications such as the polymer electrolyte membrane (PEM) water electrolyzer, which has the advantages of high operation current, high voltage efficiency, compact system design, etc. For the applications using acidic electrolytes, to reduce the cost of precious-metal oxides as the OER catalysts, researchers are developing IrO₂-based and RuO₂-based nanoparticles (NPs) with high surface-area-to-mass ratios.

At the same time, distributing the catalyst NPs on the stable and conductive support materials can help to prevent the agglomeration of catalyst NPs, provide higher electrical conductivity, and therefore maximize the effective catalytic surface area exposed to the electrolyte, which are important for the enhancement of mass activities of the precious-metal oxide OER catalysts. Currently, mesoporous carbon and their nanostructured analogs (e.g. carbon nanotubes) are widely used as the catalyst supports because of their low costs, high conductivities, large surface areas, and relatively high chemical and electrochemical stabilities in low-voltage applications such as fuel cells. However, electrolyzers and other electrochemical techniques that involve OER are usually driven in acid electrolyte up to 2.0 V versus the reversible hydrogen electrode (V RHE) to gain enough current density. Under such highly oxidative voltage, carbon materials become unstable and can be oxidized into CO₂, causing severe degradation of the electrode during OER. Therefore, no support or only non-conductive TiO₂ support was used in traditional electrolyzers, which caused higher loadings of expensive OER catalysts. Recently, several oxide materials have been studied as stable and conductive supports under high-voltage (e.g. highly oxidative) conditions for electrolyzers, including TiO₂-2h, TiC, SiC, SnO₂, and their fluorine-doped or antimony-doped forms. However, there lacks a systematic stability test of a wide spectra of candidate support materials in acid electrolyte under the OER operational condition. In addition, there lacks a deep investigation of the formal criteria for support material selection covering the cost, conductivity, stability, and other characters of the candidate materials, which is highly desirable in order to facilitate the development of long-lived catalyst supports used in acidic conditions such as those in PEM electrolyzers.
Table I. Basic properties of the materials used in this work.

| Compound          | Provider or synthesis method | BET surface area (m²/g) | Particle size (nm) | Conductivity (mS/cm) |
|-------------------|------------------------------|-------------------------|-------------------|----------------------|
| FTO Glass         | Sigma Aldrich                | -                       | -                 | -                    |
| Commercial ATO (ATO-C) | Alfa Aesar                   | 66.3                    | 11.4 ± 4.5        | 5                    |
| Synthesized ATO (ATO-S) | Sol-gel method             | 89.8                    | 3.6 ± 1.0         | 20                   |
| WO₃               | Alfa Aesar                   | 19.4                    | 67.5 ± 41.5       | 2.1 × 10⁻⁹           |
| TiCN              | Alfa Aesar                   | 21.2                    | 41.8 ± 24.6       | 51                   |
| MoO₂              | Alfa Aesar                   | 5.7                     | 247 ± 150         | 120                  |
| Mo₃O₈             | Sigma Aldrich                | 0.24                    | 2946 ± 1645       | 1.0 × 10⁻⁴           |
| Na₂MoO₄           | Alfa Aesar                   | 0.33                    | 1787 ± 1636       | 0.03                 |
| XC-72 Carbon      | Fuel Cell Earth              | -                       | -                 | 1250                 |
| AB Carbon         | Chevron                      | -                       | -                 | 245                  |
| IrO₂              | Alfa Aesar                   | 22.0                    | 19.2 ± 7.9        | 1010                 |
| RuO₂              | Sigma Aldrich                | 16.2                    | 28.7 ± 10.2       | 520                  |
| MnO₂              | Alfa Aesar                   | 19.7                    | 51.4 ± 38.5       | 5.0 × 10⁻³           |
| TiO₂              | Alfa Aesar                   | 11.9                    | 46 ± 12           | 5.2 × 10⁻⁹           |

Supplementary Information (SI) showed the prices of elements whose oxides are stable or potentially stable. The prices of some elements are low enough (shadowed in green region) to be used as major components for possible support materials while some are expensive (shadowed in yellow region), which might be used as minor components.

Materials preparation.—In this study, both commercial materials and sol-gel synthesized oxides were employed. The commercial materials include fluorine doped tin oxide (FTO) glass, MoO₃ and RuO₂ from Sigma Aldrich; ATO, IrO₂, MoO₂, TiO₂, Na₂MoO₄, TiCN and WO₃ from Alfa Aesar; XC-72 carbon from Fuel Cell Earth; and Acetylene Black (AB) carbon from Chevron. In this paper the commercial ATO is denoted as ATO-C. We also synthesized nano-sized ATO with 14% Sb doping using a sol-gel method (denoted as ATO-S), which included the following steps. First, 1.28 ml of 37% HCl was slowly added to the mixture of 0.2 g antimony (III) ethoxide and 2.88 g tin (IV) tert-butoxide under vigorous stirring. Second, the mixture was stirred at 80 °C for 1 h and the solvent was evaporated at 60 °C. Third, ATO particles were annealed in Air under 100 ml/min flow at 500 °C for 3 h to remove organics left on the surface of the particles and improve the crystallinity. The crystal structures of the ATO-S and ATO-C were characterized by X-ray diffraction (XRD) using a PANalytical X’Pert Pro powder diffractometer in the Bragg-Brentano window in the 2θ range.

Conductivity measurement.—We developed a measurement setup shown in Figure 1a to compare the electronic conductivity of support materials systematically. First, the material powders were weighted and loaded into the black plastic cell. Then two metal cylinder dies were used to lock the powders inside the cell. These two metal dies also work as the positive and negative electrodes for conductivity measurement. Impedance spectroscopy was used to measure the voltage and current applied between the metal dies under the frequency when the sample powders in the cell act as a pure resistor (with phase close to 0 during impedance measurement). During the conductivity measurement, increasing pressure was gradually applied between the two dies, which gradually compresses the powders into a condensed pellet. The pressure was controlled below 1.6 MPa. The resistance change can be recorded as a function of pressure, as shown in Figure 1b. When the pressure is high enough, the resistance becomes a roughly constant number Z, which was used to calculate the conductivity σ of the materials.

From the classic conductivity relationship without any porosity correction, we have:

\[ |Z| = \frac{l}{\sigma b^2} \]

where \( l \) is the distance between two metal dies that can be measured at the end of the measurement, and \( S \) is the cross-section area of the die that can be calculated as \( S = \pi r^2 \). Here \( r \) is the radius of the die. However, even under the highest pressure applied in this study, the porosity \( f \) of the material is still high (~10–40%, depending on materials), which leads to a much smaller conductivity measurement that needs to be corrected. In this study, the following factor \( a \) is used as an approximated porosity correction:

\[ a = \frac{\varepsilon}{b} \]

Here \( f \) could be calculated by \( f = 1 - \varepsilon \), where \( m \) is the mass of the loaded powder, and \( \rho \) is the density of the material. \( b \approx 3 \) for the spherical pore approximation. And the corrected conductivity can be written as:

\[ \sigma = \frac{al}{|Z| \pi r^2} = \frac{l}{|Z| \pi r^2} \frac{m}{\varepsilon \pi r^4} \]

Electrochemical stability test.—In this study, FTO glass was used as the substrate of supporting materials for the stability measurements because FTO itself showed higher stability in acid electrolyte under high oxidizing voltages compared with the traditional support, Ti foil. The stabilities of pure FTO glass and Ti foil in acid electrolyte were measured and compared in Figure S2. After holding at 2.0 VRHE for 1 h, FTO glass showed less capacitance change than the untreated Ti-foil. In addition, the ATO-C loaded on FTO (ATO-C@FTO) showed less capacitance change than ATO-C loaded on Ti foil (ATO-C@Ti), implying that FTO is a better substrate to support and test the candidate materials. Therefore, in this study we will only use FTO as our substrate for the stability measurement.
acting as the working electrode. All connections between FTO glass and potentiostat were covered by paraffin wax (Sigma Aldrich) to prevent etching of these parts by the acidic electrolyte. Ag/AgCl electrode was used as the reference electrode, and Pt wire as the counter electrode. The measured voltages were converted to RHE scale using H₂/H⁺ redox couple. A glass jacket outside the glass cell was used to circulate heated or cooled water in controlling the temperature of the electrolyte. The capacitance of the working electrode was measured using cyclic voltammetry (CV) measurements at 100 mV/s from 0.5 to 0.7 V_RHE in Ar-saturated 0.5 M H₂SO₄ electrolyte. This potential range is selected because most of the tested materials are electrochemically stable in this region with no OER or metal redox reactions that may affect the measurement of double-layer capacitance. The integration of total charge transfer in one CV cycle was divided by the corresponding voltage change (i.e. 0.2 V) to calculate the capacitance.

Two different voltage-holding methods were applied as the stability test in this study. One method, the simple voltage holding method, is to keep the working electrode at certain voltage for a continuous period, as shown in Figure S4a. The other method is called start-stop test, which switches the working electrode between a certain voltage and the open circuit voltage for 1 min at each voltage stage, as shown in Figure S4b. The capacitance measurement showed that the degradation of ATO-C@FTO is similar as a function of total voltage holding time in both methods (Figure S4c), implying that the voltage shift does not have clear acceleration effect to the degradation of the material. Therefore, we will only apply the voltage holding method for the stability measurement in this study.

Selected supporting materials were mixed with RuO₂ for the OER activity measurement and were deposited onto the FTO glass using the same ink drop-cast method mentioned above. The supporting material loading was 100 μg/cm²_glass, and the RuO₂ loading was also 100 μg/cm²_glass. The OER activities were measured by CV at 10 mV/s from 0.5 to 1.7 V_RHE in O₂-saturated 0.5 M H₂SO₄ electrolyte and the currents at 1.5 V_RHE were used for comparison. It is worth noticing that when conductive materials were loaded on the FTO glass, the ohmic resistance of the electrochemical test setup measured using the impedance method was between 15 and 20 Ω, with the measured current less than 3 mA. The corresponding iR drop was between 45 to 60 mV, whose difference among samples is negligible in the stability and OER activity tests.

Transmission electron microscopy.—Transmission Electron Microscopy (TEM) samples were prepared by dropping catalyst ink onto Cu grids or using grids to scratch the working electrode after OER measurements. TEM images in this work were taken on JEOL 2010F equipped with ultrahigh resolution polepiece, having a point resolution of 0.19 nm. Bright field diffraction contrast imaging was used to determine particle size distributions and general morphology of the catalyst nanoparticles. Digital images were analyzed using Gatan Digital Micrograph v2.01 (Gatan Inc.) and ImageJ v1.44p (National Institute of Health, USA). High resolution TEM (HRTEM) images were recorded without an objective aperture and were analyzed using Gatan Digital Micrograph. Parallel-beam energy dispersive spectroscopy (EDS) data were collected and the atomic composition was determined using INCA (Oxford Instruments) software. For each oxide sample, three different spots with a diameter of ~200 nm were used to collect the bulk chemical composition, while three different spots with a diameter of ~5 nm at the particle edges were used to collect the surface chemical composition. Error bars in all EDS data represent the standard deviation of the results on multiple spots. TEM images are also used in this study to determine the particle size distributions for each candidate powder. For each sample, at least 100 particles were measured to calculate the average size and the standard deviation of the particle diameter, and the results were shown in Table I.

Results and Discussion

Electrical conductivity and electrochemical capacitance measurements of candidate support materials.—Support materials must be electrical conductive to transfer the electrons during the OER in order to increase the effective electrochemical surface area. The correct conductivity measurement of supporting materials is important but challenging, since the supporting materials are in particle form with low pack density. In this paper, we specifically developed a conductivity measurement setup for the powder samples, as shown in Figure 1a, to compare the electronic conductivity of support materials systematically. The detailed measurement principle can be found in the experimental method section and in the SI. We found that the electrical conductivity is closely related to the effective electrochemical surface area. Here the effective electrochemical surface area of the candidate support material was evaluated by the measurement of electrochemical capacitance. 280 which was calculated using the CV curve measured at 100 mV/s from 0.5 to 0.7 V_RHE in Ar-saturated 0.5 M H₂SO₄ electrolyte with the oxide loading of 100 μg/cm²_glass. As shown in Figure 1c, when the measured conductivity was lower than 1 mS/cm, the measured capacitance is almost the same to the pure FTO substrate, indicating that the candidate compounds particles contribute almost no additional electrochemical effective area. This is because low conductivity will make it hard to transfer electrons to the

Figure 1. Conductivity measurement and criteria in material selection (a) Photo of the conductivity measurement setup we developed in this study. Two metal cylinder dies were used to lock and press the powders inside the cell. These two metal dies also work as the positive and negative electrodes for the conductivity measurement. (b) Two example conductivity measurement data of XC-72 carbon and ATO-C powders as a function of applied pressure using the setup shown in panel a. (c) The relationship between the initial electrochemical capacitance of the candidate materials on FTO glass and their electrical conductivity measured using the setup shown in panel a. The electrochemical capacitance was calculated using the CV curve measured at 100 mV/s from 0.5 to 0.7 V_RHE in Ar-saturated 0.5 M H₂SO₄ electrolyte. The horizontal line represents the capacitance of pure FTO glass.
surface of the candidate particles as the currents will take the path of least resistance, and therefore most of the surface area will be inert during electrochemical processes. Hence, materials with conductivity lower than 1 mS/cm will not be suitable as support materials.

In addition to the high conductivity, the support materials for OER catalysts in acidic electrolytes also require reasonable stability when holding at a highly oxidative potential in the acid solution. In this study, the stability of candidate oxide supports was evaluated by measuring the capacitance change before and after a potential holding at 2.0 \( V_{\text{RHE}} \) in the Ar-saturated 0.5 M \( \text{H}_2\text{SO}_4 \) for 1 h. Here the 2.0 \( V_{\text{RHE}} \) voltage holding is selected to develop a protocol for accelerated stability tests, which is as high as or higher than the voltages applied in previous stability studies on support materials.\(^{24,26-34}\) The corresponding current change during the voltage holding on example materials can be found in Figure S5. Figures 2a–2d showed the evolutions of CV curves before and after the voltage holding on 4 example materials. In the case of XC-72 carbon, the double-layer capacitance reduced notably after the voltage holding (see Figure 2a), implying the severe degradation of carbon supports under the highly oxidative conditions. Similar stability issue has been observed in a previous study,\(^{24}\) and is the main motivation for the development of more stable non-carbon supports.\(^{26-29}\) In comparison, the CV curve of the ATO-C sample remains almost unchanged after the same voltage holding, indicating a higher stability under the OER condition in the acid solution (see Figure 2b). The stability of the ATO under high voltages in acid electrolyte has been previously reported by Geiger et al.,\(^{30}\) with a high onset overpotential for reductive and oxidative dissolution of more than 0.4 V. Some of the candidate materials with high conductivity, such as MoO\(_2\) and TiCN, were found even less stable than the carbon materials (AB carbon and XC-72) after holding the voltage at 2.0 \( V_{\text{RHE}} \) (see Figures 2c and 2d). Figure 2e summarizes the capacitance of all the commercial candidate supports before and after the 1 h voltage holding. From Figure 2e, we found that ATO-C demonstrated the highest stability and highest electrochemical surface area among all the nonprecious-metal compounds, only lower than IrO\(_2\) and RuO\(_2\). Due to the high cost of Ir and Ru, ATO was considered the best support material among all candidates based on the stability, conductivity and economic criteria.

The ATO-C powder used in this study has an average particle size of \( \sim 11.4 \) nm (see Figure 3b). To test how the change of particle size would influence the performance of ATO as support material, we synthesized some smaller ATO particles (ATO-S) using the sol-gel method, with the average particle size of \( \sim 3.6 \) nm (see Figure 3a). The XRD results showed that the ATO-S particles have the same anatase phase as the ATO-C. The EDS results demonstrated that the synthesized ATO-S has a Sb doping level \( \sim 14\% \), similar to that of ATO-C. This means ATO-S and ATO-C have similar chemistry and atomic structure. The main difference of ATO-S from ATO-C is its smaller particle size, which is accompanied by a higher surface area. Although the increased grain boundaries in smaller particles usually lead to lower conductivity, here we found that the ATO-S has a greater conductivity (20 mS/cm), which is 4 times higher than that of ATO-C. The increased conductivity on ATO-S might be caused by better particle compacting (due to the more uniform particle size distribution) during the pressure-dependent conductivity measurement, or by more oxygen vacancies in smaller particles synthesized by sol-gel method. More studies are needed to explore the origin of the improved conductivity on ATO-S.

Due to the larger specific surface area and higher conductivity, ATO-S demonstrates higher initial capacitance in the CV measurement compared with ATO-C, as shown in Figures 4b and 4c. The capacitance of ATO-S loaded on FTO glass remained almost unchanged...
Figure 3. The basic characterizations of (a) sol-gel synthesized ATO (i.e. ATO-S), and (b) commercial ATO (i.e. ATO-C). Left panels: the particle size distributions, BET surface areas, and measured conductivities. The distribution, mean size and standard deviation of ATO particles were measured using TEM images upon over 100 particles. Middle panels: XRD patterns. Both samples showed the same anatase phase. Right panels: TEM images, electron diffraction patterns and EDS-determined Sb concentrations.

Figure 4. High-voltage and/or high-temperature stability test on (a) FTO glass, (b) ATO-C on FTO glass, and (c) ATO-S on FTO glass. The ATO loadings on the FTO glass were 100 μg/cm² glass. The upper panels showed the example CV curves used for capacitance measurement before and after the holding at 2.5 V_{RHE} for 1 h in Ar-saturated 0.5 M H₂SO₄ at 55 °C. The lower panels showed the capacitance calculated from the CV curves before and after the voltage holding at 2.0 or 2.5 V_{RHE} and at 25 or 55 °C for 1 h in Ar-saturated 0.5 M H₂SO₄. The CV curves were measured at 100 mV/s between 0.5 and 0.7 V_{RHE} in Ar-saturated 0.5 M H₂SO₄. Please notice that the scales of y axes in panel a are different from those in panel b or c, due to the relatively small capacitance of pure FTO glass.
after keeping the voltage at 2.0 V_{RHE} for 1 h, implying it was as stable as the ATO-C samples. To study the stability of ATO material under more severe conditions, we further increased the holding voltage from 2.0 to 2.5 V_{RHE}, and increased the electrolyte temperature from 25 to 55 °C (see Figure 4), which is closer to the operating temperature of practical electrolyzers.\cite{footnote41} When the voltage increased from 2.0 to 2.5 V_{RHE}, the capacitance of pure FTO glass showed noticeable increase after the voltage holding (see Figure 4a), indicating the more oxidative potential accelerated the surface corrosion of FTO glass. The capacitance change might be caused by the surface roughening during the voltage holding, which could increase the surface area of FTO glass. In comparison, increasing the electrolyte temperature from 25 to 55 °C showed little influence on the capacitance change of FTO glass, implying that a higher temperature has smaller impact to the stability of FTO during the voltage holding. For the ATO-C and ATO-S powders loaded on FTO glass, increasing the holding voltage from 2.0 to 2.5 V_{RHE} at 25 °C led to a higher capacitance loss, but the capacitance loss of ATO-S was smaller than that of ATO-C (Figures 4b and 4c). This means the synthesized ATO has higher stability than the commercial ATO under high-voltage conditions at room temperature. Moreover, when increasing the temperature from 25 to 55 °C, the influence of temperature change on the capacitance stability at 2.0 V_{RHE} was still small for both ATO-S and ATO-C, similar to that of pure FTO glass. However, after a higher voltage holding at 2.5 V_{RHE}, the capacitance loss of ATO-C reduced at the higher temperature of 55 °C. The lower capacitance loss of ATO-C at 55 °C and 2.5 V_{RHE} might be due to the compensation effect from roughening, which increased the specific surface area of the ATO particles and could compensate some of the capacitance loss due to material loss, but further study is required to explain such change.

Electrochemical capacitance and OER measurements of ATO-supported RuO₂.—To test the practical supporting performance of ATO particles, we tested the capacitance and OER activity change of RuO₂ OER catalysts supported by ATO-C or ATO-S, which was compared with the unsupported RuO₂ and RuO₂ supported by AB carbon (Figure 5). All samples were loaded on FTO glass. The loading of RuO₂ was 100 μg/cm²glass, and the loading of support material (ATO or carbon) was also 100 μg/cm²glass. After mixing RuO₂ with these support materials, the initial total capacitance increased from

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Stability tests on the capacitance and OER performance of (a)(e) RuO₂ loaded on FTO glass, (b)(f) mixture of RuO₂ and AB carbon loaded on FTO glass, (c)(g) mixture of RuO₂ and ATO-C loaded on FTO glass, and (d)(h) mixture of RuO₂ and ATO-S loaded on FTO glass. The RuO₂ loading was 100 μg/cm²glass, and the support material loading (AB carbon, ATO-C, or ATO-S) was also 100 μg/cm²glass. In (a)-(d), the upper panels showed the example CV curves used for capacitance measurement before and after the holding at 2.5 V_{RHE} for 1 h in Ar-saturated 0.5 M H₂SO₄ at 25 °C. The lower panels showed the capacitance calculated from the CV curves before and after the holding at 1.7, 2.0, or 2.5 V_{RHE} for 1 h at room temperature in Ar-saturated 0.5 M H₂SO₄. The CV curves were measured at 100 mV/s between 0.5 and 0.7 V_{RHE} in Ar-saturated 0.5 M H₂SO₄ at room temperature. (e)-(h) are the OER activity at 1.5 V_{RHE} measured before and after keeping the voltage at 1.7, 2.0, or 2.5 V_{RHE} for 1 h at 25 °C in Ar-saturated 0.5 M H₂SO₄.}
\end{figure}
RuO$_2$ under the same voltage holding condition, indicating that using 0.2 mF (Figures 5b and 5f). Both the relative activity loss and relative capacitance loss were ~30%, which could be caused by the detachment of RuO$_2$ particles from the FTO glass during the OER process. When the holding voltage was increased to 2.5 V$_{\text{RHE}}$, a much larger capacitance loss (~80%) and activity loss (~90%) can be observed after 1 h voltage holding. The poor stability observed at 2.5 V$_{\text{RHE}}$ might be caused by more physical detachments of RuO$_2$ caused by the formation of more O$_2$ gas bubbles and stronger Ru chemical dissolutions under more oxidative voltages, which have been described in the previous work.$^{35-37,42}$ When RuO$_2$ was mixed with carbon, after holding at 1.7 or 2.0 V$_{\text{RHE}}$ for 1 h, the OER activity dropped by ~65% from ~2.0 A/gRuO$_2$ to ~0.7 A/gRuO$_2$, accompanied with a capacitance drop by ~87% from ~1.55 mF to ~0.2 mF (Figures 5b and 5f). Both the relative activity loss and relative capacitance loss are much greater than those of the unsupported RuO$_2$ under the same voltage holding condition, indicating that using carbon as the support material could reduce the stability of the system during the OER. The additional capacitance and activity loss compared with the unsupported RuO$_2$ might be caused by the oxidation of carbon support to CO$_2$ in the oxidative condition$^{43}$ that leads to the additional detachment of RuO$_2$. When the holding voltage was increased to 2.5 V$_{\text{RHE}}$, an even larger capacitance loss (~90%) and activity loss (~95%) were observed, similar to the observation on the unsupported RuO$_2$, which again could be caused by the more severe RuO$_2$ detachment due to the stronger O$_2$ bubble formation or more severe RuO$_2$ dissolution under more oxidative conditions. In contrast, when using ATO-C or ATO-S to support RuO$_2$, no clear capacitance change (<10%) or activity change (<10%) were observed (Figures 5e, 5d, 5g, and 5h), even after holding at a high voltage up to 2.5 V$_{\text{RHE}}$ for 1 h at 25°C. The stabilized capacitance and OER activity can be due to the more uniform distribution of RuO$_2$ particles on the electrodes. If the RuO$_2$ particles are not closely packed together, there will be open attachments of RuO$_2$ caused by the formation of more O$_2$ gas bubbles and therefore will cause less detachment of RuO$_2$ particles. The above observations on the one hand prove the high stability of the ATO particles in acidic electrolyte and under the high-voltage condition. On the other hand, it showed that adding stable support materials could help to enhance the stability of the OER performance of RuO$_2$ catalysts, presumably by increasing the distance between RuO$_2$ particles, preventing the particle aggregation, and decreasing the mechanical detachment of catalysts due to the O$_2$ formation. It worth noticing that although in this work RuO$_2$ was used as the model OER catalysts to test the potential beneficial effects from the ATO support, previous studies have shown that ATO support also works for Ir$^{24}$ and IrO$_2$$^{25,26}$ during OER catalysis. In fact, the series of selection criteria for support materials explored in this paper should work on general OER catalysts operated in acidic electrolytes.

**Conclusions**

In this work, we systematically searched and characterized a series of compounds as the support materials for OER catalysis in acidic electrolytes. The thermodynamic stability criteria and economic criteria were discussed and applied to screen the candidate compounds that are potentially cheap and stable enough to be used as the support material for OER catalysis in acidic environment. Then the conductivity and stability tests were used to further optimize the candidate list. Finally, we identified commercial ATO as the most promising candidate support material with reasonable cost, enough conductivity, and high stability in acidic electrolyte under the highly oxidative OER potentials. Then we synthesized a nano-sized ATO by sol-gel method, with smaller particle size, larger specific surface area, and higher electrical conductivity compared with the commercial ATO. The newly-synthesized ATO brings greater and more stable improvement of OER activity to the RuO$_2$ catalysts than the commercial ATO and carbon support when used to support RuO$_2$ particles during the OER.

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