Anode reaction: [2 $H_2O(l) \rightarrow O_2(g) + 4\ H^+(aq) + 4e^-$] ------ Reaction (1)

Cathode reaction: [2 $H^+(aq) + 2e^- \rightarrow H_2(g)$] ------ Reaction (2)

Reaction 1, i.e. water oxidation, is rate limiting because it has a comparatively higher energy barrier. On the counter electrocathode, Reaction (2), i.e. proton reduction, proceeds easier because it has a much lower energy barrier. Without an efficient catalyst, a significant overpotential is required for water oxidation, resulting in low efficiency.

Extensive efforts have been made to develop efficient electrocatalysts for water oxidation. Known catalysts include cobalt-based, cobalt and manganese oxide clusters, ruthenium oxide, iridium oxide and nickel oxide electrocatalysts. However, the electrocatalytic efficiencies of these known catalysts are not promising enough to be considered economically viable for scale up operations.

Accordingly, there is a need to provide an alternative electrocatalyst for the electrolytic generation of hydrogen that overcomes or ameliorates the deficiencies discussed hereinabove.

Summary

In a first aspect, the present disclosure relates to an electrocatalyst consisting of amorphous Ru nanoparticles.

In another aspect, there is provided an electrode, when used in electrolytic water oxidation, said electrode consisting of amorphous Ru nanoparticles.

In another aspect, there is provided a method of generating hydrogen, the method comprising applying a voltage to an anode and a cathode in an electrolyte, wherein said anode consists of amorphous Ru nanoparticles.

In the present disclosure, there is provided a method of producing hydrogen, the method comprising: applying a voltage to an anode and a cathode in an electrolyte, wherein said anode consists of amorphous Ru nanoparticles disposed on a conductive support. In one embodiment, the electrolyte comprises water and the disclosed method comprises oxidizing water at the anode to yield oxygen and protons. In a particular embodiment, the electrolyte consists essentially of water. Advantageously, the disclosed method is capable of producing hydrogen in a water:hydrogen molar ratio of 1:1.

In still another aspect, there is provided a system for producing hydrogen, the system comprising a cathode and an anode electrically communicated with an electrolyte, a voltage source coupled to said cathode and anode; and wherein said anode consists of amorphous Ru nanoparticles.

Advantageously, it has been found that the amorphous Ru nanoparticles act as effective catalysts for the anode reaction of water oxidation, even when the Ru nanoparticles loading at/on the anode is in relatively low concentrations of about 10 - 30 μg per cm^2 of the anode surface. In particular, the disclosed electrocatalyst is capable of reducing or completely eliminating over-potential to the electrodes in order to facilitate the water splitting redox reactions. In particular embodiments, the disclosed method is capable of effecting the redox reactions under a potential difference of about 1.2 V – 1.5 V. Advantageously, in particular embodiments, the calculated Faradaic efficiency of the disclosed method for producing hydrogen from water is demonstrably close to about 95% to 100%, or about 99% -100%.

Furthermore, by using the disclosed electrocatalyst, the generation of hydrogen may be advantageously performed under room temperature and atmospheric pressure.

In addition, it has been found that the amorphous Ru nanoparticles can be advantageously prepared by methods that do not require costly equipment associated with RF magnetron sputtering, vapor deposition methods, electro-deposition, chemical or hydrothermal synthesis methods. Thus, the disclosed Ru electrocatalysts are cost-effective to produce and hence can be economically viable in operations. Accordingly, the present disclosure further provides a method for preparing the amorphous Ru nanoparticles and the fabrication of a Ru nanoparticle-coated electrode for use in the above disclosed electrolytic method/system of producing hydrogen.

The present disclosure further envisions applications and uses of the electrocatalyst, including but not limited to, in fuel cells and solar-powered hydrogen generators.

The total average weight loading of Ru in the Ru-coated anode may be from about 5 to about 200 μg per cm^2 anode. The average weight loading of Ru may be selected from 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110,115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195 or 200 μg per cm^2. All recited catalyst loading values may be subject to a variance of ±1, ±2, ±3, or ±4 μg per cm^2. The average weight loading of the Ru catalyst may also be in a range selected from any two recited values.

Each layer of amorphous Ru nanoparticles may comprise an average weight loading of about 5 to about 50 μg Ru per cm^2 anode. Where more than one layer of Ru nanoparticles is coated onto the anode, each Ru nanoparticle layer may independently comprise the same or different catalyst weight loading, provided that the total weight loading is as defined hereinbefore. Applying multiple coats/layers of Ru nanoparticle thin films to achieve a desired catalyst loading may advantageously improve the adhesion of the Ru nanoparticle layers to the anode support or substrate. This may avoid or mitigate the loss of catalysts during operation and handling.

The system may be advantageously integrated with a renewable energy source for supplying the potential difference across the electrodes. In a particular embodiment, the renewable energy source comprises a photovoltaic module, such as a solar cell or a solar panel.

The supplied voltage may not be particularly limited and depends on the scale of the electrolytic system. In embodiments of the present disclosure, voltages as low as 1.2 V to 1.5 V have been observed to effect electrolytic hydrogen production in the presence of the disclosed Ru electrocatalysts. In embodiments, the supplied voltage may be selected from 1.2, 1.25, 1.3, 1.35, 1.4, 1.45 or 1.5 V.

The invention illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms "comprising", "including", "containing", etc. shall be read expansively and without limitation. Additionally, the terms and expressions employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any

abundant metals, the small quantity employed in the current application makes the relative cost effective and the system favors ruthenium metal due to its excellent stability. In addition, the highly stable ruthenium thin film was optimized at 250 °C heat treatment and capable to undergo three cycles of hydrogen generation with retention of high electrolytic activity.

The inventors have for the first time demonstrated the feasibility of amorphous ruthenium nanoparticles as electrocatalysts (anode material). The nanoparticles were synthesized by a non-hydrolytic approach and spin coated on a conductive substrate for electrocatalytic water splitting.

The preparation of ruthenium nanoparticles with uniform size in a facile way is amenable to scale-up operations which are able to efficiently split water molecules into oxygen and hydrogen in stoichiometric amount. In addition to the high catalytic properties, the stability of the ruthenium nanoparticles was remarkable with no significant degradation of electrolytic activity for three consecutive cycles of electrolytic water splitting. Overall, the incorporation of ruthenium nanoparticles as anode material in electrolytic water splitting offer the benefits of high efficiency catalytic properties with excellent chemical stability that renders a long life span, particularly the electrolytic splitting of water is carried out under neutral electrolyte conditions at room temperature and atmospheric pressure.

Claims

1. An electrocatalyst consisting of amorphous Ru nanoparticles.

2. An electrode, when used in electrolytic water oxidation, said electrode consisting of amorphous Ru nanoparticles.

3. A system for producing hydrogen, said system comprising a cathode and an anode electrically communicated with an electrolyte, a voltage source coupled to said cathode and anode; and wherein said anode consists of amorphous Ru nanoparticles.

4. The system of claim 3, wherein the anode is coated with one or more layers of said amorphous Ru nanoparticles.

5. The system of claims 3 or 4, wherein the anode has an average Ru loading by weight of about 5 to about 200 μg Ru per cm^2 anode.

6. The system of any one of claims 3 to 5, wherein said electrolyte comprises water.

7. The system of any one of claims 3 to 6, wherein said amorphous Ru nanoparticles have an average particle diameter of about 1 to about 5 nm.

8. The system of any one of claims 3 to 7, wherein the voltage source comprises a photovoltaic module or solar module.

9. A method of generating hydrogen, the method comprising applying a voltage to an anode and a cathode in an electrolyte, wherein said anode consists of amorphous Ru nanoparticles.

10. The method of claim 9, wherein prior to said applying step, the method comprises a step of providing Ru nanoparticles onto a surface of said anode.