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(73) Patentee: SMOLTEK AB, Kaserntorget 7, 411 18 Göteborg SE
(72) Inventor: Vincent Desmaris, Göteborg SE
Fabian Wenger, Göteborg SE
(74) Agent: Kransell & Wennborg KB, Box 2096, 403 12, Göteborg SE

(54) Title: An electrolyzer and a method for producing a catalyst supported on a nanostructure

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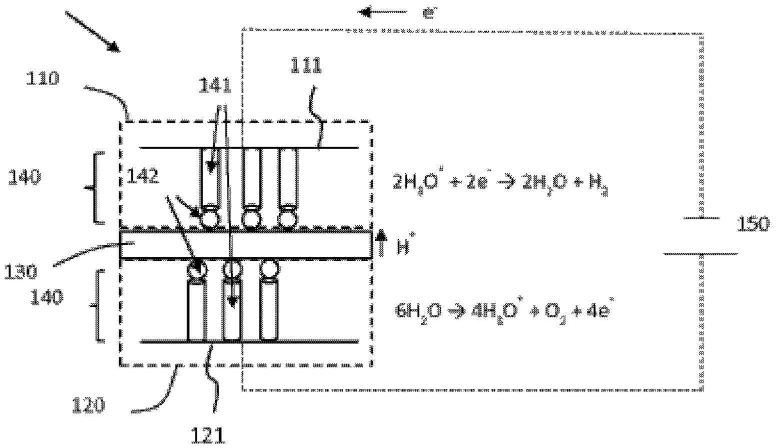
(57) Abstract:

An electrolyzer (100) comprising a first (110) and a second (120) electrode and an ion exchange membrane (13) arranged in-between the first and the second electrode is disclosed. Each electrode comprises a conductive element (111, 121). At least one of the electrodes comprises a catalyst structure (140), the catalyst structure comprising a plurality of elongated nanostructures (141) arranged to connect the conductive element (111,121) to a corresponding plurality of catalyst particles (142). Each catalyst particle (142) is localized at an end of a respective elongated nanostructure (141) opposite from the conductive element (111,121).



ABSTRACT

An electrolyzer (100) comprising a first (110) and a second (120) electrode and an ion exchange membrane (13) arranged in-between the first and the second electrode is disclosed. Each electrode comprises a conductive element (111, 121). At least one of the electrodes comprises a catalyst structure (140), the catalyst structure comprising a plurality of elongated nanostructures (141) arranged to connect the conductive element (111,121) to a corresponding plurality of catalyst particles (142). Each catalyst particle (142) is localized at an end of a respective elongated nanostructure (141) opposite from the conductive element (111,121).

TITLE

An electrolyzer and a method for producing a catalyst supported on a nanostructure

TECHNICAL FIELD

The present disclosure relates to devices used in electrolysis, particularly for the electrolysis of water.

BACKGROUND

The production of hydrogen gas through the electrolysis of water is a promising technology both for replacing the production of hydrogen gas from fossil fuels and as a means of converting excess electrical energy from intermittent energy sources such as solar and wind power to chemical energy for storage. However, existing water electrolyzers suffer from problems related to the corrosive conditions within the electrolysis cell and the use of expensive catalysts. For electrolysis cells comprising ion exchange membranes it may be necessary to use catalysts comprising e.g., platinum or iridium, which entails a significant cost. Additionally, current electrolysis cells are limited in terms of the ion current per area through the cell. An improvement in this regard would result in increased production capability.

WO2018185617 discloses a water electrolyzer comprising platinum or platinum oxide as a catalyst for the electrolysis reactions.

Still, there is a need for improved water electrolyzers.

SUMMARY

It is an object of the present disclosure to provide improved electrolyzers.

This object is at least in part obtained by an electrolyzer comprising a first and a second electrode and an ion exchange membrane arranged in-between the first and second electrode. Each electrode comprises a conductive element and at least one of the electrodes comprises a catalyst structure. The catalyst structure comprises a plurality of elongated nanostructures arranged to connect the conductive element to a corresponding plurality of catalyst particles. Each catalyst particle is localized at an end of a respective elongated nanostructure opposite from the conductive element.

Advantageously, each catalyst particle being localized at an end of a respective elongated nanostructure provides an improved control over the position of the catalyst particles relative to the ion exchange membrane and other components of the electrolyzer, which makes it possible to achieve a more efficient operation. As an example, the catalyst particles need to be in close proximity to the ion exchange membrane and present a large surface area in order to efficiently promote the chemical reactions comprised in the electrolysis process. With improved control over the position of the catalyst particles, both the distance to the ion exchange membrane and the exposed surface area can be adjusted to improve performance.

Advantageously, since a larger fraction of the catalyst particles can be reliably positioned close to the ion exchange membrane, the total number of catalyst particles used can be reduced compared to electrolyzers where the catalyst structure does not afford the same degree of control over the position of catalyst particles. In other words, in the electrolyzer disclosed here a smaller amount of catalyst particles may be used to achieve the same efficiency as in previously known electrolyzers.

According to aspects, the conductive elements may be conductive plates. Conductive plates are commonly used with electrolyzers, it is an advantage that the techniques disclosed herein may be implemented with the same form factor.

According to aspects, the elongated nanostructures may comprise carbon nanostructures. Advantageously, carbon nanostructures have good electrical conductivity and structural stability, thereby providing both control over the position of the catalyst particle and a good electrical connection between the conductive elements and the catalyst particles, which is beneficial for efficient electrolyzer operation. The elongated carbon nanostructures may comprise any of carbon nanofibers, carbon nanotubes, and/or carbon nanowires.

Carbon nanofibers, as well as carbon nanotubes and nanowires, have the advantage of being easy to grow on a wide range of substrates.

In particular, for carbon nanofibers, the shape and surface structure can be altered by adjusting the conditions under which the nanofibers are grown. This provides the possibility of creating a plurality of nanofibers that are arranged in a particularly suitable configuration. They are also structurally and chemically robust.

The process of growing carbon nanostructures may entail the use of a growth catalyst to promote the formation of the carbon nanostructure. Advantageously, the growth catalyst used to grow carbon nanofibers may comprise the same materials as the catalyst particles used to promote the chemical reactions comprised in the electrolysis process. If the same materials can be used as a growth catalyst and as electrolysis catalyst particles, fabrication of the electrolyzer may be made simpler and more efficient.

According to aspects, the catalyst particles are positioned less than 10 nm from the ion exchange membrane, or preferably less than 5 nm from the ion exchange membrane. According to other aspects, the catalyst particles are positioned in contact with the ion exchange membrane, or within 0.1-1nm from the ion exchange membrane. Advantageously, positioning the catalyst particles in close proximity to the ion exchange membrane, i.e., less than 10 nm, and preferably closer, allows more efficient use of the catalyst particles, as the hydrogen or hydroxide ions generated during the reactions can more easily enter the ion exchange membrane. Also, hydrogen or hydroxide ions exiting the ion exchange membrane can more easily adsorb to a catalyst particle, which is important for the electrolysis reactions.

According to aspects, the elongated nanostructures may extend generally along respective axes, where the axes are oriented in parallel to each other and extended substantially perpendicularly to the conductive element. This means that the catalyst particles localized to the end of each elongated nanostructure form a layer of catalyst particles that can all simultaneously be positioned in close proximity to the ion exchange membrane. A larger fraction of the catalyst particles will then be in close proximity to the ion exchange membrane compared to a configuration where the axes are not oriented in parallel, leading to an increase in efficiency without the need to use more catalyst particles. Alternately, a smaller amount of catalyst particles can be used without a reduction in efficiency.

It is appreciated that the elongated nanostructures are not perfectly straight. The elongated nanostructure extending along an axis should be understood to mean that the height axis of the nanostructure extends in the general direction of the axis.

According to aspects, the catalyst structure comprises a porous carbon material. According to other aspects, at least one of the elongated nanostructures may be a branched nanostructure comprising a trunk and at least two branches, where a catalyst particle is localized at the end of each branch. Advantageously, branched nanostructures make it possible to increase the number of catalyst particles per unit area of the ion exchange membrane, thereby increasing the surface area of catalyst where the electrolysis reactions may take place.

According to aspects, at least one section of an elongated nanostructure may be covered by a protective coating arranged to increase a resistance to corrosion. The chemical environment at the electrodes of an electrolyzer is corrosive, especially at the anode side of the ion exchange membrane. Applying a protective coating to the elongated nanostructures is thus an advantage as it reduces wear and allows the catalyst structure to be used for longer. According to aspects, the protective coating may comprise any of platinum, iridium, or titanium, or a combination thereof.

The object is also obtained at least in part by a method of producing a catalyst structure for an electrolyzer. The electrolyzer comprises a first and a second electrode and an ion exchange membrane arranged in-between the first and second electrode. Each electrode comprises a conductive element. The method comprises generating a plurality of elongated nanostructures, the elongated nanostructures being connected to one of the conductive elements. The method also comprises attaching a plurality of catalyst particles to the plurality of elongated nanostructures such that each catalyst particle is localized at an end of a respective elongated nanostructure opposite from the conductive element.

Advantageously, the elongated nanostructures being connected to the conductive element ensures good electrical contact between the conductive element and the catalyst particles, which is important for efficient electrolyzer operation. Each catalyst particle being localized at an end of a respective elongated nanostructure provides control over the position of the catalyst particle, e.g., in relation to the ion exchange membrane.

According to aspects, generating a plurality of elongated nanostructures may comprise growing the elongated nanostructures on a substrate. Growing the elongated nanostructures on a substrate presents the advantage that the properties and shape of the nanostructures can be tailored by tuning the conditions under which the nanostructures are grown, in order to improve the functionality of the resulting catalyst structure. As an example, the thickness of the elongated nanostructures could be tuned to improve structural stability. As another example, the surface of the nanostructures could be altered to include structure such as ridges and grooves, which increases the total surface area and may provide more possible sites at which catalyst particles may be attached.

According to aspects, growing the elongated nanostructures on a substrate may comprise depositing a growth catalyst layer on a surface of the substrate and growing the elongated nanostructures on the growth catalyst layer. The growth catalyst layer promotes growth of the elongated nanostructures. By altering the properties of the growth catalyst layer, the properties of the grown elongated nanostructures can be tuned in order to improve the functionality of the resulting catalyst structure.

According to further aspects, depositing a growth catalyst layer may comprise depositing a uniform growth catalyst layer and introducing a pattern onto the deposited uniform growth catalyst layer. An advantage of introducing a pattern onto the deposited uniform growth catalyst layer is that it makes it possible to control the density of nanostructures per surface area on the substrate. The density of nanostructures per surface area may affect the flow of fluids such as water, oxygen gas, and hydrogen gas, to and from the catalyst particles. It may also affect the density of catalyst particles per surface area of the membrane. Both the flow and the catalyst particle density impact the efficiency of the electrolyzer. As such, controlling the density of nanostructures per surface area of the substrate makes it possible to improve the efficiency of the electrolyzer.

According to aspects, growing the elongated nanostructures on a substrate may comprise depositing a conducting layer on a surface of the substrate. Advantageously, depositing a conducting layer on the surface of the substrate can produce the effect of electrically grounding the substrate. Electrically grounding the substrate may be advantageous for certain methods of growing nanostructures. If a conductive layer is deposited on a surface of the substrate and a growth catalyst layer is deposited on top of the conductive layer, the conductive layer may also hinder diffusion of atoms and/or molecules between the catalyst layer and the substrate.

The object is also obtained at least in part by a method of producing a catalyst structure for an electrolyzer, where the electrolyzer comprises a first and a second electrode, as well as an ion exchange membrane arranged in-between the first and the second electrode. Each electrode comprises a conductive element. The method comprises configuring a substrate having a surface and selecting a growth catalyst for the growth of elongated nanostructures on the substrate. The growth catalyst is selected such that it can also be used as an electrolysis catalyst in the electrolyzer. The method also comprises depositing a growth catalyst layer comprising the selected growth catalyst on the surface of the substrate and generating elongated nanostructures with a catalyst particle suitable for use in an electrolyzer localized at an end of each elongated nanostructure by growing elongated nanostructures on the growth catalyst layer.

In addition to the advantages described above associated with growing elongated nanostructures on a substrate using a catalyst layer, this method presents the further advantage of using a growth catalyst that can also be used as an electrolysis catalyst in an electrolyzer. This makes it possible to produce the catalyst structure in a simpler and more efficient way.

According to aspects, depositing a growth catalyst layer may comprise depositing a uniform growth catalyst layer and introducing a pattern onto the deposited uniform growth catalyst layer. An advantage of introducing a pattern onto the deposited uniform growth catalyst layer is that it makes it possible to control the density of nanostructures per surface area on the substrate. The density of nanostructures per surface area may affect the flow of fluids such as water, oxygen gas, and hydrogen gas, to and from the catalyst particles. It may also affect the density of catalyst particles per surface area of the membrane. Both the flow and the catalyst particle density impact the efficiency of the electrolyzer. As such, controlling the density of nanostructures per surface area of the substrate makes it possible to improve the efficiency of the electrolyzer.

According to aspects, the method may comprise depositing a conducting layer on a surface of the substrate. Advantageously, depositing a conducting layer on the surface of the substrate can produce the effect of electrically grounding the substrate. Electrically grounding the substrate may be advantageous for certain methods of growing nanostructures. If a conductive layer is deposited on a surface of the substrate and a growth catalyst layer is deposited on top of the conductive layer, the conductive layer may also hinder diffusion of atoms and/or molecules between the catalyst layer and the substrate.

Generally, all terms used in the claims are to be interpreted according to their ordinary meaning in the technical field, unless explicitly defined otherwise herein. All references to "a/an/the element, apparatus, component, means, step, etc." are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any method disclosed herein do not have to be performed in the exact order disclosed, unless explicitly stated. Further features of, and advantages with, the present invention will become apparent when studying the appended claims and the following description. The skilled person realizes that different features of the present invention may be combined to create embodiments other than those described in the following, without departing from the scope of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will now be described in more detail with reference to the appended drawings, where:

Figure 1 schematically illustrates an electrolyzer,

Figures 2A-B show catalyst structures,

Figure 3 schematically illustrates an energy harvesting system, and

Figures 4A-B are flow charts illustrating methods.

DETAILED DESCRIPTION

Aspects of the present disclosure will now be described more fully with reference to the accompanying drawings. The different devices and methods disclosed herein can, however, be realized in many different forms and should not be construed as being limited to the aspects set forth herein. Like numbers in the drawings refer to like elements throughout.

The terminology used herein is for describing aspects of the disclosure only and is not intended to limit the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise.

Although the following description is focused on electrolyzers suitable for the electrolysis of water, a person skilled in the art will realize that the devices and methods herein described can also be used for electrolysis of other liquids or gases, provided that the reduction and oxidation reactions comprised in the electrolysis process take place on the surface of a catalyst and that the electrodes are separated by a solid electrolyte.

An electrolyzer comprises two electrodes, of which one is the positively charged anode and one is the negatively charged cathode, and a medium which allows for transport of ions, known as an electrolyte. The electrodes are connected to a power supply which provides electrical energy, driving the electrolysis reaction.

In some electrolyzers, a solid electrolyte or ion exchange membrane is used as the ion transport medium. An ion exchange membrane is a solid material that can be traversed by ions. Since this material conducts ions it can also be known as an ionic conductor. Use of ion exchange membranes allows for a compact electrolyzer design, as well as good separation of oxygen and hydrogen gas, which is an advantage.

The ion exchange membranes used in electrolyzers can be categorized according to the ionic species moving through the membrane. Anion exchange membranes, AEM, conduct the negative anion, in this case the hydroxide ion, from the cathode to the anode. Proton exchange membranes, PEM, conduct the positive hydrogen ion or proton from the anode to the cathode. Both anion and proton exchange membranes may be permeable to water but minimize the amount of hydrogen and / or oxygen gas that travels between the electrodes.

In electrolyzers comprising ion exchange membranes, each electrode comprises an electrically conductive element connected to the power source and an electrolysis catalyst that facilitates the chemical reactions comprised in the electrolysis process. The electrolysis catalyst may be in the form of discrete particles, henceforth referred to in this description as catalyst particles, in which case the electrode may also comprise a support structure that connects the conductive element and the electrolysis catalyst while still being permeable to water and gases.

Herein, a conductive element is an element that has a high electric conductivity. A high electric conductivity could be an electric conductivity normally associated with metallic or semiconducting materials, or an electric conductivity of more than 100 $(\Omega m)^{-1}$.

A catalyst is a material or chemical compound that facilitates a chemical reaction, e.g., by lowering the amount of energy needed to start the chemical reaction. An electrolysis catalyst facilitates chemical reactions comprised in the electrolysis process, such as the reaction taking place at the anode side or the reaction taking place at the cathode side. The anode- and cathode-side electrolysis catalysts will frequently comprise different materials.

In general, the support structure needs to be able to conduct electricity in addition to being chemically stable under the conditions present in the electrolyzer. The support structure could for example have an electric conductivity comparable to that of a metal or a semiconductor. Metallic materials such as a porous titanium mesh may be used. It is also common to use porous carbon, carbon paper, or materials comprising carbon fibers.

During electrolysis, water enters the electrolyzer on the side of the ion exchange membrane where the anode is located. For a PEM electrolyzer, water molecules that come into contact with the electrolysis catalyst on the anode side undergo the reaction:

$$2\mathrm{H_2O} \rightarrow 4\mathrm{H}^+ + \mathrm{O}_2 + 4e^-.$$

The electrons will enter the circuit connecting the two electrodes, the oxygen gas leaves the electrolyzer, and the protons will diffuse across the PEM to the cathode side and the cathode electrolysis catalyst, where they undergo the reaction:

$$4\mathrm{H}^+ + 4e^- \rightarrow 2\mathrm{H}_2.$$

In an AEM electrolyzer, the water molecules will instead first diffuse through the AEM to the cathode side, where the following reaction takes place at the cathode electrolysis catalyst:

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2.$$

The hydroxide ions will diffuse through the AEM and undergo the following reaction at the anode electrolysis catalyst:

$$4OH^- - 4e^- \rightarrow O_2 + 2H_2O.$$

For optimal operation of an ion exchange membrane electrolyzer, the electrolysis catalyst needs to be in close proximity to the ion exchange membrane so that protons or hydroxide ions can easily enter the ion exchange membrane. As electron transport to and from the electrolysis catalyst is essential for the reactions, the electrolysis catalyst also needs to be in electrical contact with the conductive elements. Additionally, the electrolysis catalyst must have enough exposed surface area that water molecules can easily adsorb to it and gas molecules can desorb.

If the electrolysis catalyst comprises particles supported by a support structure, any particle that is too far from the ion exchange membrane or has poor electric contact with the conductive element will contribute little or not at all to the electrolysis reactions, thereby lowering the efficiency of the electrolyzer. It is thus an advantage to be able to control the position of the catalyst particles.

Figure 1 shows an electrolyzer 100 comprising a first 110 and a second 120 electrode, and an ion exchange membrane 130 arranged in-between the first and the second electrode. Each electrode comprises a conductive element 111, 121 and at least one of the electrodes comprises a catalyst structure 140. The catalyst structure comprises a plurality of elongated nanostructures 141 arranged to connect the conductive element 111, 121 to a corresponding plurality of catalyst particles 142, where each catalyst particle 142 is localized at an end of a respective elongated nanostructure 141 opposite from the conductive element 111, 121. Both conductive elements are electrically connected to a power source 150.

Here, the conductive elements 111, 121 comprise conductive materials that can withstand the chemical environment in the electrolyzer. The conductive elements 111, 121 may for example comprise materials such as titanium, tungsten, and / or zirconium. Optionally, a conductive element may be a steel element coated with one or a combination of titanium, tungsten, and zirconium. A conductive element may also comprise a carbon composite material.

As an example, the conductive elements 111, 121 may be conductive plates. A plate is taken to mean an object that is extended in two dimensions and comparatively thin in the third dimension. The conductive elements 111, 121 may also be in the shape of a sheet, or other structure suitable for electrolysis.

The ion exchange membrane comprises ionic conductors, i.e., materials through which ions can travel. As an example, the ionic conductor may be a polymer such as sulfonated tetrafluoroethylene, also known as Nafion, or polymers based on polysulfone or polyphenole oxide. However, the ion exchange membrane may also comprise other types of ionic conductors, for example metal oxides such as doped barium zirconate, doped barium cerate, doped lanthanum gallate, or stabilized zirconia.

The catalyst particles comprise materials that are catalytically active and promote the reactions taking place at the cathode and anode during electrolysis. As an example, the catalyst particles may comprise platinum, ruthenium, palladium, or iridium. The catalyst particles may also comprise metal oxides such as platinum oxide or iridium oxide. As another example, the catalyst particles may comprise cobalt or nickel. Optionally the catalyst particles may be nanoparticles, i.e., have a size that is substantially smaller than one micrometer and mostly between 1 and 100 nm. Preferably, the catalyst particles may be between 3 and 10 nm in size.

For the electrolyzer to operate efficiently, ions must be able to enter the ion exchange membrane from the catalyst surface where the chemical reactions take place, which requires the catalyst particles to be in close proximity to the ion exchange membrane 130. For example, the catalyst particles 141 may be positioned less than one micrometer from the ion exchange membrane 130.

Alternatively, the catalyst particles 142 may be positioned less than 10 nm from the ion exchange membrane 130, or preferably less than 5 nm from the ion exchange membrane 130. Alternatively, the catalyst particles 142 may be positioned in contact with the ion exchange membrane 130.

According to yet other aspects, the catalyst particles 142 may be distributed such that the number of catalyst particles per unit volume is highest less than one micrometer from the ion exchange membrane and decreases as the distance from the ion exchange membrane increases.

It should be noted that the surface of the ion exchange membrane may exhibit surface structure, such as pores, grooves, and ridges, on a scale that is larger than the size of the catalyst particles. In this case, the distance between a catalyst particle and the ion exchange membrane surface is taken to be the shortest distance to the ion exchange membrane surface in any direction.

A nanostructure is a structure having a size that is substantially smaller than one micrometer, and preferably between 1 and 100 nm, in at least one dimension. Herein, an elongated nanostructure is a nanostructure that is substantially larger in at least one dimension, such as height, compared to another dimension such as width or depth. As an example, consider a substantially cylindrical nanostructure characterized by a height and a radius. The nanostructure may be considered elongated if the height is significantly larger than the radius, e.g., if the height is more than twice as large as the radius. Similar reasoning may be applied to nanostructures that are substantially conical, rectangular, or of arbitrary shape.

The elongated nanostructures 141 may for example be straight, spiraling, branched, wavy or tilted. Optionally, they may be classifiable as nanowires, nano-horns, nanotubes, nano-walls, crystalline nanostructures, or amorphous nanostructures.

According to aspects, the elongated nanostructures 141 may comprise carbon nanostructures. For example, the elongated nanostructures 141 may comprise any of, carbon nanofibers, carbon nanotubes, and/or carbon nanowires. The elongated nanostructures 141 may also comprise a combination of two or more of carbon nanofibers, carbon nanotubes, and / or carbon nanowires. As an example, an elongated carbon nanostructure could comprise carbon nanotubes attached to a carbon nanofiber. An elongated carbon nanostructure could also be a graphene wall.

For carbon nanofibers, the shape and surface structure can be tuned by adjusting the conditions under which the nanofibers are grown in order to improve the functionality of the resulting catalyst structure 140. As an example, the thickness of the nanofibers could be tuned to improve structural stability. It is also possible to grow nanofibers that are arranged in a configuration that is particularly suitable for the catalyst structure 140, e.g., with regard to the density of nanofibers per surface area, or the orientation of the nanofibers.

It is also possible to tune the available surface area or the number of carbon atoms per surface area. As an example, carbon nanofibers may be partly formed by amorphous carbon, resulting in a higher number of carbon atoms per surface area. This may result in a larger number of possible sites where catalyst particles 142 can be attached. A similar effect may be achieved if the carbon nanofibers have a corrugated surface structure. Herein, a corrugated surface structure is taken to mean that a surface has a series of grooves and ridges of similar or different sizes.

Furthermore, the process of growing carbon nanofibers may involve the use of a growth catalyst that promotes formation of carbon nanofibers. The growth catalyst may comprise materials that are also comprised in the catalyst particles used to promote the chemical reactions comprised in the electrolysis process. If the same material can be used as a growth catalyst and as an electrolysis catalyst forming catalyst particles, fabrication of the electrolyzer may be made simpler and more efficient.

According to other aspects, the elongated nanostructures 141 may comprise copper, aluminum, silver, gallium arsenide, zinc oxide, indium phosphate, gallium nitride, indium gallium nitride, indium gallium arsenide, silicon, or other materials.

Since the nanostructures are elongated nanostructures 141, they are larger in one dimension than in other dimensions. Consider an axis along this dimension as the height axis of the nanostructure. If this height axis extends perpendicularly or nearly perpendicularly to the conductive element 111, 121, the elongated nanostructures can be considered as extending along an axis 210 that is perpendicular to the conductive element 111, 121, as shown in Figure 2A.

This should not be taken to mean that the nanostructures are completely straight or completely perpendicular to the conductive element 111, 121, as they can for example have a moderate tilt relative to the axis 210, or they may curve back and forth to form a spiraling or wavy shape. Rather, the nanostructures extend in the general direction of the axis 210. In this context, a moderate tilt mean that the angle between the height axis and the axis 210 is less than 45 degrees, and preferably may be less than 30 degrees.

For the elongated nanostructures 141 to effectively connect the conductive element 111, 121 to the catalyst particles 142, it is advantageous to have them extend from the conductive element 111, 121 in a uniform direction. Thus, the elongated nanostructures 141 may extend generally along respective axes 210, where the axes are oriented in parallel to each other and extended substantially perpendicularly to the conductive element 111, 121.

The catalyst structure 140 must also allow a sufficient flow of water and of oxygen and hydrogen gas to and from the catalyst particles and the ion exchange membrane. To improve the flow of water and gases it may be advantageous to use other structures in addition to the elongated nanostructures. As an example, the catalyst structure 140 may comprise a porous carbon material. A porous carbon material could for example be carbon microfiber cloth or carbon paper. This porous carbon material may be placed adjacent to the conductive element 111, 121, with elongated nanostructures 141 extending from the porous carbon material towards the ion exchange membrane 130.

When considering the flow of water and gases through the catalyst structure, it should be noted that closely spaced elongated nanostructures may impede the water flow, but an increase in the number of catalyst particles per unit area of the ion exchange membrane 130 may be beneficial as it would make a larger amount of electrolysis catalyst available for the electrolysis reactions. Therefore, it is advantageous to use a branched nanostructure such as the one shown schematically in Figure 2B. Each branch of the nanostructure has one catalyst particle localized at one end, in proximity to the ion exchange membrane. As each nanostructure has multiple branches, this means that the number of catalyst particles per unit area of the ion exchange membrane 130 can be increased without placing the elongated nanostructures more closely together.

Thus, according to aspects, at least one of the elongated nanostructures 141 may be a branched nanostructure comprising a trunk 201 and at least two branches 202, where a catalyst particle is localized at the end of each branch 202.

The chemical environment in an electrolyzer may be corrosive, especially on the anode side due to the high electrical potential. To prevent degradation of the catalyst structure 140, the elongated nanostructures 141 may be shielded from the surrounding chemical environment. For example, at least one section of an elongated nanostructure 141 may be covered by a protective coating arranged to increase a resistance to corrosion. As an example, the protective coating may comprise any of platinum, iridium, or titanium, or a combination thereof. As another example, the protective coating may comprise ceramic materials or metal oxides such as aluminum oxide, cerium oxide and zirconium oxide.

According to aspects, the surface of the elongated nanostructures 141 may also be chemically altered to achieve hydrophobic or hydrophilic surface properties. This may be achieved through a number of methods such as coating, etching, or chemical functionalization.

Figure 3 shows the electrolyzer 100 incorporated into an energy harvesting system 300 comprising, in addition to the electrolyzer 100, an energy source 310 and a hydrogen storage device 320. Although the example given in Figure 3 is an energy source 310 comprising solar cells, other energy sources such as hydropower or wind power may also be used. The energy harvesting system 300 may be particularly useful for storing excess energy from intermittent energy sources such as solar cells and wind power in the form of hydrogen gas.

With reference to Figure 4A and Figure 1, there is also disclosed a method of producing a catalyst structure 140 for an electrolyzer 100. The electrolyzer 100 comprises a first 110 and a second 120 electrode and an ion exchange membrane 130 arranged in-between the first and the second electrode. Each electrode comprises a conductive element 111, 121. The method comprises generating SA1 a plurality of elongated nanostructures 141, the elongated nanostructures 141 being connected to a conductive element 111, 121. The method further comprises attaching SA2 a plurality of catalyst particles 142 to the plurality of elongated nanostructures 141 such that each catalyst particle 142 is localized at an end of a respective elongated nanostructure 141 opposite from the conductive element 111, 121.

Attaching SA2 catalyst particles 142 to elongated nanostructures 141 may be accomplished through methods such as sputtering, chemical vapor deposition, or other methods.

Elongated nanostructures 141 may be generated through lithographic methods such as colloidal lithography or nanosphere lithography, focused ion beam machining and laser machining, among other methods. For nanofibers comprising carbon or organic compounds, methods such as electrospinning or chlorination of carbides such as titanium carbide or metalloorganic compounds such as ferrocene may also be used.

According to aspects, generating SA1 a plurality of elongated nanostructures 141 may comprise growing SA11 the elongated nanostructures 141 on a substrate. Growing SA11 elongated nanostructures 141 on a substrate allows extensive tailoring of the properties of the nanostructures. For instance, the growth conditions may be selected to increase the surface area of each nanostructure. According to aspects, the elongated nanostructures may be grown in a plasma.

The substrate may comprise materials such as silicon, glass, stainless steel, ceramics, silicon carbide, or any other suitable substrate material. The substrate may also comprise high temperature polymers such as polymide. Optionally, the substrate may be a component of the electrolyzer 100, such as a conductive plate 111, 121 or the ion exchange membrane 130.

Growing SA11 the elongated nanostructures 141 on a substrate may comprise depositing a growth catalyst layer on one surface of the substrate and growing SA11 the elongated nanostructures 141 on the growth catalyst layer.

Herein, a growth catalyst is a substance that is catalytically active and promotes the chemical reactions comprised in the formation of nanostructures.

The growth catalyst may comprise materials such as nickel, iron, platinum, palladium, nickel-silicide, cobalt, molybdenum, gold, or alloys thereof. As an example, the growth catalyst layer may be between 1 and 100 nm thick. As another example, the growth catalyst layer may comprise a plurality of particles of growth catalyst.

Growing SA11 the elongated nanostructures 141 on the growth catalyst layer may comprise heating the growth catalyst layer to a temperature where nanostructures can form and providing a gas comprising a reactant in such a way that the reactant comes into contact with the growth catalyst layer. Here, the reactant is a chemical compound or mix of chemical compounds that comprises the chemical elements used to form the nanostructure. For a carbon nanostructure, the reactant may comprise a hydrocarbon such as methane or acetylene, or it may comprise carbon monoxide.

According to aspects, the growth catalyst materials and the parameters of the growth process may be selected to achieve so-called tip growth of the nanostructures. During tip growth, a nanostructure will grow beneath a section of the growth catalyst, resulting in an elongated nanostructure with a remaining particle of growth catalyst at the tip of the elongated nanostructure.

Attaching SA2 catalyst particles 142 to the elongated nanostructures 141 may be accomplished using the remaining particle of growth catalyst. As an example, chemical elements present in the remaining particle of growth catalyst may be replaced with other chemical elements through methods such as galvanic replacement. As another example, the remaining particle of growth catalyst may be selectively coated with an electrolysis catalyst material suitable for use in the electrolyzer 100.

According to aspects, depositing a growth catalyst layer may comprise spin coating the surface of the substrate with particles of growth catalyst. According to other aspects, depositing a growth catalyst layer comprises depositing a uniform growth catalyst layer and introducing a pattern onto the deposited uniform growth catalyst layer. Introducing a pattern onto the deposited uniform growth catalyst layer could comprise altering the thickness of the growth catalyst layer according to a pattern, or selectively removing the growth catalyst layer in some places. Introducing a pattern onto the growth catalyst layer may for example be accomplished through lithographic methods such as colloidal or nanosphere lithography. The patterning of the growth catalyst layer makes it possible to control the density of nanostructures per surface area on the substrate.

According to aspects, growing SA11 the elongated nanostructures on a substrate comprises depositing a conducting layer on a surface of the substrate. The growth catalyst layer may then be deposited on top of the conducting layer. After growing the elongated nanostructures, parts of the conductive layer that extend between or around the elongated nanostructures may be selectively removed. This removal may for example be accomplished through etching, e.g., plasma etching, pyrolysis etching or electrochemical etching.

The conducting layer electrically grounds the substrate, which is an advantage for certain methods of nanostructure growth such as growth in a plasma. It may also prevent the diffusion of atoms between the growth catalyst layer and the substrate.

According to aspects, the conducting layer may be between 1 and 100 microns thick.

According to aspects, additional layers may be present in addition to the substrate, the growth catalyst layer, and the conducting layer. The materials comprised in the additional layers may be selected to tune properties of the grown nanostructures, facilitate vertically oriented growth, or otherwise improve the result of the growth process. The additional layers may also comprise a conducting element 111, 121 forming part of an electrode 110, 120 for an electrolyzer 100.

According to aspects, depositing any layer including the conducting layer and the growth catalyst layer may be carried out by methods such as evaporating, plating, sputtering, molecular beam epitaxy, pulsed laser depositing, chemical vapor deposition, spin-coating, spray-coating, or other suitable methods.

As an example, producing a catalyst structure 140 may comprise generating SA1 elongated nanostructures by depositing a conducting layer on an upper surface of a substrate; depositing a layer of growth catalyst on the conducting layer; growing the elongated nanostructures 141 on the layer of growth catalyst; and selectively removing the conducting layer between and around the elongated nanostructures. It may also comprise attaching SA2 catalyst particles 142 to the elongated nanostructures following the growth process.

According to aspects, the elongated nanostructures may be grown on a substrate comprising a component of the electrolyzer 100, such as one of the conductive elements 111, 121 or the ion exchange membrane 130. According to other aspects, the elongated nanostructures may be grown on some other substrate and subsequently transferred onto for example one of the conductive elements 111, 121 or the ion exchange membrane 130.

Figure 4B shows a flowchart of a second method of producing a catalyst structure 140 for an electrolyzer 100, where the electrolyzer 100 comprises a first 110 and a second 120 electrode, and an ion exchange membrane 130 arranged in-between the first and the second electrode. Each electrode comprises a conductive element 111, 121. The method comprises configuring SB0 a substrate having a surface and selecting SB1 a growth catalyst for the growth of elongated nanostructures on the substrate. The growth catalyst is selected such that it can also be used as an electrolysis catalyst in the electrolyzer 100. The method also comprises depositing SB2 a growth catalyst layer comprising the selected growth catalyst on the surface of the substrate and generating SB3 elongated nanostructures 141 with a catalyst particle 142 suitable for use in an electrolyzer 100 localized at an end of each elongated nanostructure 141 by growing SB31 elongated nanostructures 141 on the growth catalyst layer.

In addition to the previously described advantages of growing elongated nanostructures on a substrate, such as being able to tailor the properties of the nanostructures, this method has the advantage of simplifying the production of the catalyst structure 140 by using the same material in the growth catalyst as in the electrolysis catalyst particles 142. Attaching catalyst particles to the elongated nanostructures is thus not done in a separate step.

The substrate may comprise materials such as silicon, glass, stainless steel, ceramics, silicon carbide, or any other suitable substrate material. The substrate may also comprise high temperature polymers such as polymide.

The growth catalyst may comprise materials such as nickel, iron, platinum, palladium, nickel-silicide, cobalt, molybdenum, gold, or alloys thereof. As an example, the growth catalyst layer may be between 1 and 100 nm thick. As another example, the growth catalyst layer may comprise a plurality of particles of growth catalyst.

To select a growth catalyst that is also suitable for use as an electrolysis catalyst in an electrolyzer 100, it is preferred to find materials that can successfully act as catalysts for both the growth process and the chemical reactions comprised in the electrolysis process. Examples of suitable materials may be platinum, palladium, and nickel, which are used both in growth catalysts for growing nanostructures and in electrolysis catalysts.

Growing SB31 the elongated nanostructures 141 on the growth catalyst layer may comprise heating the growth catalyst layer to a temperature where nanostructures can form and providing a gas comprising a reactant in such a way that the reactant comes into contact with the growth catalyst layer. Here, the reactant is a chemical compound or mix of chemical compounds that comprises the chemical elements used to form the nanostructure. For a carbon nanostructure, the reactant may comprise a hydrocarbon such as methane or acetylene, or it may comprise carbon monoxide.

According to aspects, the elongated nanostructures may be grown in a plasma.

According to aspects, the growth catalyst materials and the parameters of the growth process may be selected to achieve so-called tip growth of the nanostructures. During tip growth, a nanostructure will grow beneath a section of the growth catalyst, resulting in an elongated nanostructure with a remaining particle of growth catalyst at the tip of the elongated nanostructure.

As an example, a substrate may be configured SB0 to comprise one of the conductive elements 111, 121 of an electrolyzer electrode 110, 120 and a growth catalyst may be selected SB1 such that it can also be used as an electrolysis catalyst. If, after depositing SB2 the growth catalyst layer, the parameters of the growth process are tuned to achieve tip growth, growing SB31 elongated nanostructures on the growth catalyst layer will result in a plurality of elongated nanostructures attached to a conductive element with a catalyst particle localized at one end of each elongated nanostructure, opposite from the conductive element.

Depositing a growth catalyst layer SB2 may also comprise depositing a uniform growth catalyst layer and introducing SB22 a pattern onto the deposited uniform growth catalyst layer. As previously mentioned, introducing a pattern onto the deposited uniform growth catalyst layer could comprise altering the thickness of the growth layer according to a pattern, or selectively removing the growth catalyst layer in some places. Introducing a pattern onto the growth catalyst layer may for example be accomplished through lithographic methods such as colloidal or nanosphere lithography. The patterning of the growth catalyst layer makes it possible to control the density of nanostructures per surface area on the substrate

The method may also comprise depositing SB21 a conducting layer on a surface of the substrate. The growth catalyst layer may be deposited on top of the conducting layer. After growing the elongated nanostructures, parts of the conductive layer that extend between or around the elongated nanostructures may be selectively removed. This removal may for example be accomplished through etching, e.g., plasma etching, pyrolysis etching or electrochemical etching. According to aspects, the conducting layer may be between 1 and 100 microns thick.

The conducting layer electrically grounds the substrate, which is an advantage for certain methods of nanostructure growth such as growth in a plasma. It may also prevent the diffusion of atoms between the growth catalyst layer and the substrate.

According to aspects, additional layers may be present in addition to the substrate, the growth catalyst layer, and the conducting layer. The materials comprised in the additional layers may be selected to tune properties of the grown nanostructures, facilitate vertically oriented growth, or otherwise improve the result of the growth process. The additional layers may also comprise a conducting element 111, 121 forming part of an electrode 110, 120 for an electrolyzer 100.

According to aspects, depositing any layer including the conducting layer and the growth catalyst layer may be carried out by methods such as evaporating, plating, sputtering, molecular beam epitaxy, pulsed laser depositing, chemical vapor deposition, spin-coating, spray-coating, or other suitable methods.

According to aspects, the elongated nanostructures may be grown on a substrate comprising a component of the electrolyzer 100, such as one of the conductive elements 111, 121 or the ion exchange membrane 130. According to other aspects, the elongated nanostructures may be grown on some other substrate and subsequently transferred onto for example one of the conductive elements 111, 121 or the ion exchange membrane 130.

CLAIMS

1. An electrolyzer (100) comprising a first (110) and a second (120) electrode and an ion exchange membrane (130) arranged in-between the first and the second electrode, each electrode comprising a conductive element (111, 121), at least one electrode comprising a catalyst structure (140), the catalyst structure comprising a plurality of elongated nanostructures (141) arranged to connect the conductive element (111,121) to a corresponding plurality of catalyst particles (142), where each catalyst particle (142) is localized at an end of a respective elongated nanostructure (141) opposite from the conductive element (111,121), **characterized by that** at least one section of an elongated nanostructure (141) is covered by a protective coating arranged to increase a resistance to corrosion.

2. The electrolyzer according to claim 1, wherein the elongated nanostructures (141) comprise carbon nanostructures.

3. The electrolyzer (100) according to claim 2, where the elongated carbon nanostructures (141) comprise any of: carbon nanofibers, carbon nanotubes, and/or carbon nanowires.

4. The electrolyzer (100) according to any previous claim, wherein the catalyst particles (142) are positioned less than 10 nm from the ion exchange membrane (130), and preferably less than 5 nm from the ion exchange membrane.

5. The electrolyzer (100) according to claim 4, wherein the catalyst particles (142) are positioned in contact with the ion exchange membrane (130).

6. The electrolyzer (100) according to any previous claim, wherein the elongated nanostructures (141) extend generally along respective axes, where the axes are oriented in parallel to each other and extended substantially perpendicularly to the conductive element (111,121).

7. The electrolyzer (100) according to any previous claim, wherein the catalyst structure (140) comprises a porous carbon material.

8. The electrolyzer (100) according to any previous claim, wherein at least one of the elongated nanostructures (141) is a branched nanostructure comprising a trunk (201) and at least two branches (202), where a catalyst particle is localized at the end of each branch (202).

9. The electrolyzer according to any previous claim, wherein the protective coating comprises any of platinum, iridium, or titanium, or a combination thereof.

10. The electrolyzer according to any previous claim, wherein the conductive elements (111, 121) are conductive plates.

11. A method of producing a catalyst structure (140) for an electrolyzer (100), the electrolyzer (100) comprising a first (110) and a second (120) electrode and an ion exchange membrane (130) arranged in-between the first and the second electrode, each electrode comprising a conductive element (111, 121), the method comprising:

generating (SA1) a plurality of elongated nanostructures (141), the elongated nanostructures (141) being connected to the conductive element (111, 121) comprised in the first or second electrode (110, 120);

attaching (SA2) a plurality of catalyst particles (142) to the plurality of elongated nanostructures (141) such that each catalyst particle (142) is localized at an end of a respective elongated nanostructure (141) opposite from the conductive element (111,121) comprised in the first or second electrode (110, 120);

the method being characterized by that it comprises

covering at least one section of an elongated nanostructure (141) with a protective coating arranged to increase a resistance to corrosion.

12. The method according to claim 11, wherein generating (SA1) a plurality of elongated nanostructures (141) comprises growing (SA11) the elongated nanostructures (141) on a substrate, such as on one of the

conductive elements (111, 121) comprised in the first or second electrode, on the ion exchange membrane (130), or on some other substrate.

13. The method according to claim 12, where growing (SA11) the elongated nanostructures (141) on a substrate comprises depositing a growth catalyst layer on a surface of the substrate and growing the elongated nanostructures (141) on the growth catalyst layer.

14. The method according to claim 13, where depositing a growth catalyst layer comprises depositing a uniform growth catalyst layer and introducing a pattern onto the deposited uniform growth catalyst layer.

15. The method according to any of claims 12 to 14, where growing (SA11) the elongated nanostructures (141) on a substrate comprises depositing a conducting layer on a surface of the substrate.

16. A method of producing a catalyst structure (140) for an electrolyzer (100), the electrolyzer (100) comprising a first (110) and a second (120) electrode, and an ion exchange membrane (130) arranged in-between the first and the second electrode, where each electrode comprises a conductive element (111, 121), the method comprising:

configuring (SB0) a substrate, wherein the substrate may be one of the conductive elements (111, 121) comprised in the first or second electrode, or may be the ion exchange membrane (130), or may be some other substrate, the substrate having a surface;

selecting (SB1) a growth catalyst for the growth of elongated nanostructures on the substrate, such that the growth catalyst can also be used as an electrolysis catalyst in the electrolyzer (100);

depositing (SB2) a growth catalyst layer comprising the selected growth catalyst on the surface of the substrate;

generating (SB3) elongated nanostructures (141) with a catalyst particle (142) suitable for use in an electrolyzer (100) localized at an end of each elongated nanostructure (141) by growing elongated nanostructures

(141) on the growth catalyst layer; **the method being characterized by that it comprises**

covering at least one section of an elongated nanostructure (141) with a protective coating arranged to increase a resistance to corrosion.

17. The method according to claim 16, where depositing a growth catalyst layer (SB2) comprises depositing a uniform growth catalyst layer and introducing (SB22) a pattern onto the deposited uniform growth catalyst layer.

18. The method according to any of claims 16 or 17, where depositing (SB2) a growth catalyst layer on the surface of the substrate comprises depositing (SB21) a conducting layer on the surface of the substrate.

I följande bilaga finns en översättning av patentkraven till svenska. Observera att det är patentkravens lydelse på engelska som gäller.

A Swedish translation of the patent claims is enclosed. Please note that only the English claims have legal effect.

1. En elektrolysanordning (100) innefattande en första (110) och en andra (120) elektrod och ett jonbytarmembran (130) anordnat mellan den första och den andra elektroden, vari varje elektrod innefattar ett ledande element (111, 121), där minst en elektrod innefattar en katalysatorstruktur (140), katalysatorstrukturen innefattande ett flertal avlånga nanostrukturer (141) anordnade att ansluta det ledande elementet (111, 121) till ett motsvarande flertal katalyspartiklar (142), där varje katalyspartikel (142) är lokaliserad i en ände av den respektive avlånga nanostrukturen (141) mittemot det ledande elementet (111, 121), **kännetecknad av att** åtminstone en sektion av en avlång nanostruktur (141) är täckt av en skyddande beläggning anordnad att öka en beständighet mot korrosion.

2. En elektrolysanordning enligt krav 1, vari de avlånga nanostrukturerna (141) omfattar kolnanostrukturer.

3. En elektrolysanordning enligt krav 2, där de avlånga kolnanostrukturerna (141) innefattar något av: kolnanofiber, kolnanorör, och/eller kolnanotrådar.

4. En elektrolysanordning (100) enligt något av föregående krav, vari katalyspartiklarna (142) är placerade mindre än 10 nm från jonbytarmembranet (130), och företrädesvis mindre än 5 nm från jonbytarmembranet.

5. En elektrolysanordning (100) enligt krav 4, vari katalyspartiklarna (142) är placerade i kontakt med jonbytarmembranet (130).

6. En elektrolysanordning (100) enligt något av föregående krav, vari de avlånga nanostrukturerna (141) utsträcker sig generellt längs respektive axlar, där axlarna är orienterade parallellt med varandra och utsträcker sig väsentligen vinkelrätt mot det ledande elementet (111, 121).

7. En elektrolysanordning (100) enligt något av föregående krav, vari katalysatorstrukturen (140) innefattar ett poröst kolmaterial.

8. En elektrolysanordning (100) enligt något av föregående krav, vari åtminstone en av de avlånga nanostrukturerna (141) är en grenad nanostruktur omfattande en stam (201) och åtminstone två grenar (202), där en katalyspartikel är lokaliserad vid änden av varje gren (202).

9. En elektrolysanordning enligt något av föregående krav, vari den skyddande beläggningen omfattar något av platina, iridium, eller titan, eller en kombination därav.

10. En elektrolysanordning enligt något av föregående krav, vari de ledande elementen (111, 121) är ledande plattor.

11. En metod för att framställa en katalysatorstruktur (140) för en elektrolysanordning (100), varvid elektrolysanordningen (100) innefattar en första (110) och en andra (120) elektrod och ett jonbytarmembran (130) anordnat mellan den första och den andra elektroden, där varje elektrod innefattar ett ledande element (111, 121), där metoden innefattar:

> att generera (SA1) ett flertal avlånga nanostrukturer (141), där de avlånga nanostrukturerna (141) är anslutna till det ledande elementet (111, 121) som är innefattat i den första eller andra elektroden (110, 120);
>
> att fästa (SA2) ett flertal katalyspartiklar (142) vid flertalet avlånga nanostrukturer (141) så att varje katalyspartikel (142) är lokaliserad vid en ände av en respektive avlång nanostruktur (141) mittemot det ledande elementet (111, 121) som är innefattat i den första eller andra elektroden (110, 120); **där metoden kännetecknas av att den innefattar**
>
> att täcka åtminstone en sektion av en avlång nanostruktur (141) med en skyddande beläggning anordnad att öka en beständighet mot korrosion.

12. Metoden enligt krav 11, där att generera (SA1) ett flertal avlånga nanostrukturer (141) innefattar att växa (SA11) de avlånga nanostrukturerna (141) på ett substrat, såsom på ett av de ledande elementen (111, 121) som ingår i den första eller andra elektroden, på jonbytarmembranet (130), eller på något annat substrat.

13. Metoden enligt krav 12, där att växa (SA11) de avlånga nanostrukturerna (141) på ett substrat omfattar att applicera ett tillväxtkatalysatorskikt på en yta hos substratet och att växa de avlånga nanostrukturerna (141) på tillväxtkatalysatorskiktet.

14. Metoden enligt krav 13, där att applicera ett tillväxtkatalysatorskikt omfattar applicering av ett jämnt tillväxtkatalysatorskikt och påförande av ett mönster på det applicerade jämna tillväxtkatalysatorskiktet.

15. Metoden enligt något av krav 12 till 14, där att växa (SA11) de avlånga nanostrukturerna (141) på ett substrat innefattar applicering av ett ledande skikt på en yta hos substratet.

16. En metod för att framställa en katalysatorstruktur (140) för en elektrolysanordning (100), elektrolysanordningen (100) innefattande en första (110) och en andra (120) elektrod och ett jonbytarmembran (130) anordnat mellan den första och den andra elektroden, där varje elektrod innefattar ett ledande element (111, 121), varvid metoden innefattar:

att konfigurera (SB0) ett substrat, där substratet kan vara ett av de ledande elementen (111, 121) som ingår i den första eller andra elektroden, eller kan vara jonbytarmembranet (130), eller kan vara något annat substrat, där substratet har en yta;

att välja (SB1) en tillväxtkatalysator för växande av avlånga nanostrukturer på substratet, på så sätt att tillväxtkatalysatorn också kan användas som en elektrolyskatalysator i elektrolysanordningen (100);

att applicera (SB2) ett tillväxtkatalysatorskikt innefattande den valda tillväxtkatalysatorn på substratets yta;

att generera (SB3) avlånga nanostrukturer (141) med en katalyspartikel (142) lämplig för användning i en elektrolysanordning (100) lokaliserad vid änden av varje avlång nanostruktur (141) genom att växa avlånga nanostrukturer (141) på tillväxtkatalysatorskiktet; **där metoden kännetecknas av att den innefattar**

att täcka åtminstone en sektion av en avlång nanostruktur (141) med en skyddande beläggning anordnad att öka en beständighet mot korrosion.

17. Metoden enligt krav 16, där appliceringen av ett tillväxtkatalysatorskikt (SB2) innefattar applicering av ett jämnt tillväxtkatalysatorskikt och påförande (SB22) av ett mönster på det applicerade jämna tillväxtkatalysatorskiktet.

18. Metoden enligt något av krav 16 eller 17, där applicering (SB2) av ett tillväxtkatalysatorskikt på substratets yta innefattar applicering (SB21) av ett ledande skikt på substratets yta.

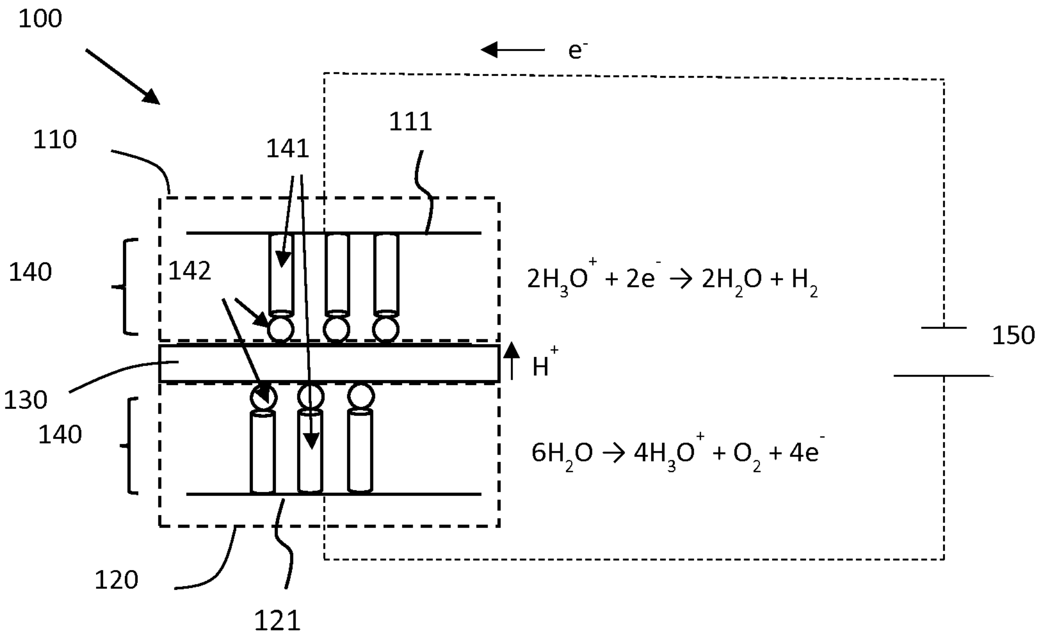


Figure 1

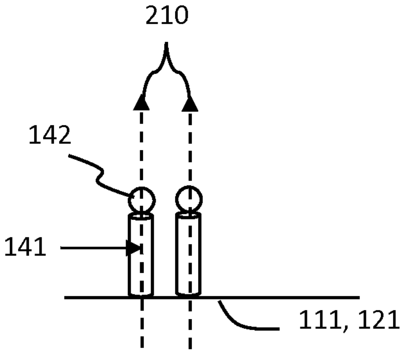


Figure 2A

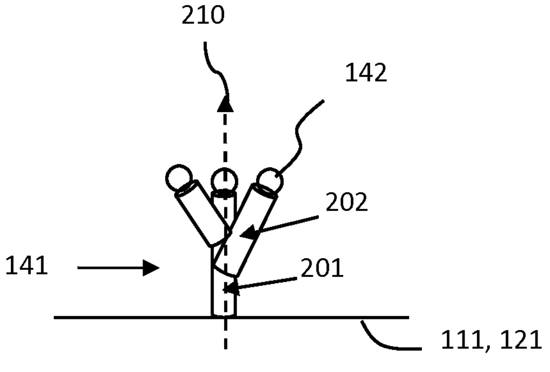


Figure 2B

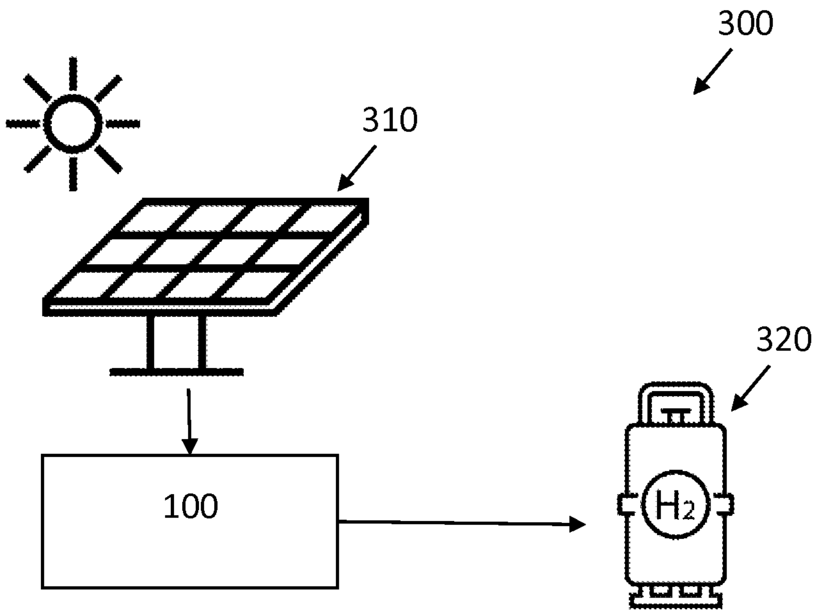


Figure 3

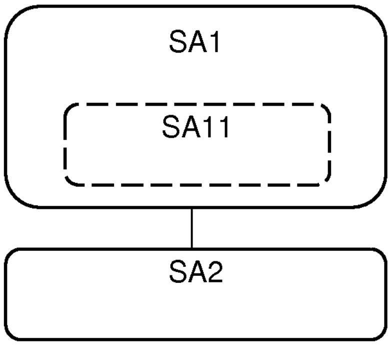


Figure 4A

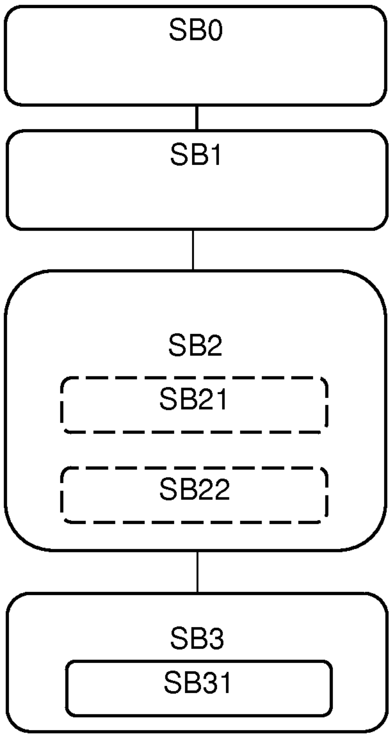


Figure 4B