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Inventor(s)

KITCHAEV; Daniil A. et al.

### CHEMICAL AND ELECTROCHEMICAL CELL ELECTRONICS PROTECTION SYSTEM

#### Abstract

An electrochemical cell active hydrogen capture and release system including a first zone having a target predetermined concentration of hydrogen c1 and housing: an electrical component, an adsorbing electrode including a hydrogen adsorbing material, a counter electrode separated from the adsorbing electrode, and an electric circuit connecting the adsorbing and counter electrodes to apply electrical bias configured to facilitate capture and release of hydrogen gas from the adsorbing electrode; and a second zone having a target predetermined concentration of hydrogen c2, c2 being greater than c1.

**Inventors:** KITCHAEV; Daniil A. (Newton, MA), KORNBLUTH; Mordechai (Brighton, MA), GADELRAH; Karim (Boston, MA), MAILLOA; Jonathan (Cambridge, MA), TUFFILE; Charles (Swansea, MA)

**Applicant:** Robert Bosch GmbH (Stuttgart, DE)

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 17/692,343, filed Mar. 11, 2022, now pending, the disclosure of which is hereby incorporated in its entirety by reference herein.

### **TECHNICAL FIELD**

[0002] The present disclosure relates to materials and systems to be utilized for prevention of hydrogen contamination of electronic components in chemical and electrochemical cells and methods of using the same.

### **BACKGROUND**

[0003] Various electronic components of chemical and electrochemical systems are routinely exposed to high concentrations of hydrogen gas. Avoiding the buildup of hydrogen pressure in the hydrogen-based chemical and electrochemical systems is a requirement especially near electronic components since electronic damage and electrical discharge negatively impact system performance. The hydrogen gas negatively influences function and lifetime of the digital components. As chemical and electrochemical systems are becoming an increasingly popular source of electrical energy, the protection of the electronic components requires new solutions.

### **SUMMARY**

[0004] In at least one embodiment, an electrochemical cell active hydrogen capture and release system is disclosed. The system may include a first zone having a target predetermined concentration of hydrogen  $c_1$  and housing: an electrical component, an adsorbing electrode including a hydrogen adsorbing material, a counter electrode separated from the adsorbing electrode, and an electric circuit connecting the adsorbing and counter electrodes to apply electrical bias configured to facilitate capture and release of hydrogen gas from the adsorbing electrode. The system may also include a second zone having a target predetermined concentration of hydrogen  $c_2$ ,  $c_2$  being greater than  $c_1$ . A hydrogen-permeable solid dielectric may form a physical separation between the counter and adsorbing electrodes. A physical diffusion barrier may form a physical separation between the first and second zones. The adsorbing electrode may include a bulk portion and a surface portion having one or more adsorbing sites. The adsorbing sites may include one or more doping sites. The electrical component may be a central processing unit. The hydrogen adsorbing material may include sites activatable by the electric circuit.

[0005] In another embodiment, an electrochemical cell active hydrogen capture and release system is disclosed. The system may include an adsorbing electrode, structured to capture and release hydrogen atoms. The adsorbing electrode may include a bulk portion having a hydrogen adsorption capacity  $a_1$  and a surface portion including one or more activatable hydrogen adsorption sites having hydrogen adsorption capacity  $a_2$ ,  $a_1 < a_2$ . The system may further include an external electric field structured to apply electric field normal to a plane of the adsorbing electrode to activate the hydrogen adsorption sites for hydrogen capture. The system may also include a grounding counter electrode. The bulk portion may include graphene. The one or more activatable hydrogen adsorption sites may include a defective graphene having a doping atom M. The doping atom M may be an element in the d-block of the Periodic Table of elements. The doping atom M may be located in an octatomic graphene ring. The one or more activatable hydrogen adsorption sites may include a nitrogen atom embedded in a graphene structure.

[0006] In yet another embodiment, an electrochemical system is disclosed. The system may include an electrical circuit, an adsorbing electrode, having one or more adsorbing sites, connected to the electrical circuit. The system may also include one or more digital components in proximity of the adsorbing electrode. The system may have a first mode of the electrical circuit increasing hydrogen adsorption capacity of the one or more adsorbing sites such that hydrogen molecules present in the system are captured by the one or more adsorbing sites to reduce hydrogen concentration near one or more digital components of the system from  $c_x$  to  $c_y$ ,  $c_y < c_x$ . The system may have a second mode of the electrical circuit reducing the hydrogen adsorption capacity of the one or more adsorbing sites such that the captured hydrogen is released from the adsorbing electrode. The first mode may include the electrical circuit configured to apply electric field normal to a plane of the adsorbing electrode. The second mode may include the electrical circuit configured to change direction of the electric field. The change may include the field reversal. The first mode may include the electrical circuit configured to polarize hydrogen molecules present in the system. The one or more adsorbing sites may include a defective graphene having a doping atom M. The hydrogen concentration relative to one or more digital components of the system may remain  $c_y$  in the second mode.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 shows a schematic depiction of a prior art electrochemical cell with electronics components and a physical diffusion barrier;

[0008] FIG. 2A shows a schematic depiction of a non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation according to one or more embodiments disclosed herein;

[0009] FIG. 2B shows a schematic depiction of another non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation;

[0010] FIG. 2C shows a schematic depiction of another non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation;

[0011] FIG. 3 shows a schematic depiction of a non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation in a first or proton exchange state;

[0012] FIG. 4 shows a schematic depiction of a non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation in a second or sorption state;

[0013] FIG. 5 shows a schematic depiction of a non-limiting example of an electrochemical cell with a sorbent and a sorbent encapsulation in a third or regeneration state;

[0014] FIGS. 6A and 6B show non-limiting examples of a chemical or electrochemical system structured to achieve hydrogen capture and minimize hydrogen build up in hydrogen poor or free zone of the system;

[0015] FIGS. 7A, 7B, and 7C show non-limiting examples of hydrogen capture material of adsorbing electrode of the systems depicted in FIGS. 6A and 6B; and

[0016] FIG. 8 shows a schematic depiction of a non-limiting example of an electrochemical cell with a hydrogen pump.

### DETAILED DESCRIPTION

[0017] Embodiments of the present disclosure are described herein. It is to be understood, however, that the disclosed embodiments are merely examples and other embodiments may take various and alternative forms. The figures are not necessarily to scale; some features could be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present embodiments. As those of ordinary skill in the art will understand, various features illustrated and described with reference to any one

of the figures may be combined with features illustrated in one or more other figures to produce embodiments that are not explicitly illustrated or described. The combinations of features illustrated provide representative embodiments for typical applications. Various combinations and modifications of the features consistent with the teachings of this disclosure, however, could be desired for particular applications or implementations.

[0018] Except in the examples, or where otherwise expressly indicated, all numerical quantities in this description indicating amounts of material or conditions of reaction and/or use are to be understood as modified by the word “about” in describing the broadest scope of the invention. Practice within the numerical limits stated is generally preferred. Also, unless expressly stated to the contrary: percent, “parts of,” and ratio values are by weight; the description of a group or class of materials as suitable or preferred for a given purpose in connection with the invention implies that mixtures of any two or more of the members of the group or class are equally suitable or preferred; description of constituents in chemical terms refers to the constituents at the time of addition to any combination specified in the description, and does not necessarily preclude chemical interactions among the constituents of a mixture once mixed.

[0019] The first definition of an acronym or other abbreviation applies to all subsequent uses herein of the same abbreviation and applies mutatis mutandis to normal grammatical variations of the initially defined abbreviation. Unless expressly stated to the contrary, measurement of a property is determined by the same technique as previously or later referenced for the same property.

[0020] It must also be noted that, as used in the specification and the appended claims, the singular form “a,” “an,” and “the” comprise plural referents unless the context clearly indicates otherwise. For example, reference to a component in the singular is intended to comprise a plurality of components.

[0021] As used herein, the term “substantially,” “generally,” or “about” means that the amount or value in question may be the specific value designated or some other value in its neighborhood. Generally, the term “about” denoting a certain value is intended to denote a range within  $\pm 5\%$  of the value. As one example, the phrase “about 100” denotes a range of  $100 \pm 5$ , i.e. the range from 95 to 105. Generally, when the term “about” is used, it can be expected that similar results or effects according to the invention can be obtained within a range of  $\pm 5\%$  of the indicated value. The term “substantially” may modify a value or relative characteristic disclosed or claimed in the present disclosure. In such instances, “substantially” may signify that the value or relative characteristic it modifies is within  $\pm 0\%$ ,  $0.1\%$ ,  $0.5\%$ ,  $1\%$ ,  $2\%$ ,  $3\%$ ,  $4\%$ ,  $5\%$  or  $10\%$  of the value or relative characteristic.

[0022] It should also be appreciated that integer ranges explicitly include all intervening integers. For example, the integer range 1-10 explicitly includes 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10. Similarly, the range 1 to 100 includes 1, 2, 3, 4, . . . 97, 98, 99, 100. Similarly, when any range is called for, intervening numbers that are increments of the difference between the upper limit and the lower limit divided by 10 can be taken as alternative upper or lower limits. For example, if the range is 1.1 to 2.1 the following numbers 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 2.0 can be selected as lower or upper limits.

[0023] In the examples set forth herein, concentrations, temperature, and reaction conditions (e.g., pressure, pH, flow rates, etc.) can be practiced with plus or minus 50 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples. In a refinement, concentrations, temperature, and reaction conditions (e.g., pressure, pH, flow rates, etc.) can be practiced with plus or minus 30 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples. In another refinement, concentrations, temperature, and reaction conditions (e.g., pressure, pH, flow rates, etc.) can be practiced with plus or minus 10 percent of the values indicated rounded to or truncated to two significant figures of the value provided in the examples.

[0024] For all compounds expressed as an empirical chemical formula with a plurality of letters

and numeric subscripts (e.g., CH.sub.2O), values of the subscripts can be plus or minus 50 percent of the values indicated rounded to or truncated to two significant figures. For example, if CH.sub.2O is indicated, a compound of formula C.sub.(0.8-1.2)H.sub.(1.6-2.4)O.sub.(0.8-1.2). In a refinement, values of the subscripts can be plus or minus 30 percent of the values indicated rounded to or truncated to two significant figures. In still another refinement, values of the subscripts can be plus or minus 20 percent of the values indicated rounded to or truncated to two significant figures. The terms “compound” and “composition” are used interchangeably.

[0025] As used herein, the term “and/or” means that either all or only one of the elements of said group may be present. For example, “A and/or B” means “only A, or only B, or both A and B”. In the case of “only A”, the term also covers the possibility that B is absent, i.e. “only A, but not B”.

[0026] It is also to be understood that this invention is not limited to the specific embodiments and methods described below, as specific components and/or conditions may, of course, vary.

Furthermore, the terminology used herein is used only for the purpose of describing particular embodiments of the present invention and is not intended to be limiting in any way.

[0027] The term “comprising” is synonymous with “including,” “having,” “containing,” or “characterized by.” These terms are inclusive and open-ended and do not exclude additional, unrecited elements or method steps.

[0028] The phrase “consisting of” excludes any element, step, or ingredient not specified in the claim. When this phrase appears in a clause of the body of a claim, rather than immediately following the preamble, it limits only the element set forth in that clause; other elements are not excluded from the claim as a whole.

[0029] The phrase “consisting essentially of” limits the scope of a claim to the specified materials or steps, plus those that do not materially affect the basic and novel characteristic(s) of the claimed subject matter.

[0030] With respect to the terms “comprising,” “consisting of,” and “consisting essentially of,” where one of these three terms is used herein, the presently disclosed and claimed subject matter can include the use of either of the other two terms.

[0031] The term “one or more” means “at least one” and the term “at least one” means “one or more.” The terms “one or more” and “at least one” include “plurality” as a subset.

[0032] The description of a group or class of materials as suitable for a given purpose in connection with one or more embodiments implies that mixtures of any two or more of the members of the group or class are suitable. Description of constituents in chemical terms refers to the constituents at the time of addition to any combination specified in the description, and does not necessarily preclude chemical interactions among constituents of the mixture once mixed. First definition of an acronym or other abbreviation applies to all subsequent uses herein of the same abbreviation and applies mutatis mutandis to normal grammatical variations of the initially defined abbreviation. Unless expressly stated to the contrary, measurement of a property is determined by the same technique as previously or later referenced for the same property.

[0033] Chemical and electrochemical systems utilizing hydrogen as a fuel source are considered the energy systems of the future either in direct hydrogen combustion engines or fuel cells. These hydrogen-producing devices are becoming increasingly popular due to their ability to produce clean energy. The systems may include fuel cells, electrolysis cells or electrolyzers, and battery cells. Fuel cells, or electrochemical cells, that convert chemical energy of a fuel (e.g. H.sub.2) and an oxidizing agent into electricity through a pair of electrochemical half (redox) reactions, have become an increasingly popular hydrogen-fuel-generating technology. Fuel cells are now a promising alternative transportation technology capable of operating without emissions of either toxins or green-house gases. An electrolyzer is an electrochemical device designed to convert electricity and water into hydrogen and oxygen, which may be in turn used to store energy. The electrolyzer utilizes electrolysis for hydrogen production. Besides fuel cells, the electrolyzer may be utilized in other applications including industrial, residential, and military applications and

technologies focused on energy storage such as electrical grid stabilization from dynamic electrical sources including wind turbines, solar cells, or localized hydrogen production.

[0034] The environment in these systems is highly corrosive. Identifying suitable materials for individual components of the cells has been a challenge in the industry. In these systems, especially control over hydrogen leakage and hydrogen pressure buildup in various system components is of high importance to meet high levels of performance and safety. In the presence of hydrogen, hydrides formation and hydrogen doping may be present especially under conditions of accelerated reactions such as high pressure and temperature.

[0035] The highly corrosive environment also negatively impacts control electronics present in the systems and cells. Control electronics in the cells such as in hydrogen fuel-cell vehicles may be located near environments containing high partial pressures of H<sub>2</sub> gas, for example in the high hydrogen anode. For example, the hydrogen recirculation pump at the fuel cell must be immediately adjacent to the primary hydrogen input to the fuel cell. Traditionally, the electronics used to control this pump, or another fuel cell-adjacent component, are in immediate proximity to the hydrogen stream, where the risk of exposure to concentrated H<sub>2</sub> is relatively high.

Exposure of electronic components to hydrogen-rich atmosphere is known to cause changes in the components' properties. The formed phases of material hydrides may alter the electronic properties of semiconducting devices or mechanical properties of structural components. For example, the doping levels of semiconductors may be negatively influenced. The degradation of many electronics components may be thus accelerated, for example, through the formation of the metal hydrides at metal contacts and/or the hydrogen embrittlement of structural metals.

[0036] Moreover, the performance and degradation of electronic components in hydrogen-rich atmosphere is not routinely tested or guaranteed by suppliers. This may result in undesirable uncertainty in the lifetime of the product.

[0037] Typically, control electronics have been isolated from the hydrogen stream in an electrochemical environment through a physical diffusion barrier. A schematic depiction of an electrochemical cell **10** with the physical diffusion barrier **12** is shown in FIG. **1**. The cell **10** includes a first chamber **A 14**, where one or more electronics components **16** are located and presence of hydrogen is undesirable. The chamber **A 14** is separated from the chamber **B 18**, where hydrogen is supposed to be present. The cell **10** further contains typical electrochemical cell portions such as the electrolyte or proton electrolyte **20**, and catalysts on the anode and cathode sides. Depicted here is the hydrogen oxidation reaction (HOR) catalyst **22** on the anode side and hydrogen evolution reaction (HER) catalyst **24** on the cathode side.

[0038] The diffusion barrier **12** typically lacks sufficient effectiveness and H<sub>2</sub> leakage through the diffusion barrier **12** is relatively high. The influx of hydrogen through the barrier **12** typically increases at higher temperatures and over an extended period of time. But leakage of hydrogen through the barrier **12** towards the electronics **16** may be problematic even at ambient temperatures over a long period of time.

[0039] Alternatively, hermetic seals, passive seals, pressure release systems, and barrier coatings have been tested and implemented to minimize permeation of hydrogen gas towards the electronics components. But hydrogen tends to leak through any barrier given its small atomic size. As such, neither seal or coating has proven to be sufficiently effective and/or reliable, especially over extended periods of time.

[0040] Therefore, there is a need to secure protection of the electronics, such as controls electronics, in the electrochemical cells such as a hydrogen fuel cell powertrain, and gain and maintain control over hydrogen leakage and buildup in system components of chemical and electrochemical systems. In addition, the protection mechanism should be efficient, affordable, and dimensionally appropriate for the chemical and/or electrochemical cell environment. The protection mechanism should not waver in effectiveness during fluctuating temperature and/or pressure ranges and for an extended period of time.

[0041] In one or more embodiments, a hydrogen capture and release system is disclosed. The system includes a chemical or an electrochemical cell **100**. The cell **100** may be a fuel cell, electrolyzer cell, battery cell. A non-limiting example of the cell **100** is shown in FIGS. 2A-2C. The cell **100** has a chamber A **114** including one or more electronics components **116**, schematically depicted. Presence of hydrogen or hydrogen stream is not desirable in the chamber A **114** such that concentration of hydrogen in chamber A is 0 or  $c_1$  which is a predetermined value, lower than concentration of hydrogen  $c_2$  which is present in chamber B. Chamber A thus has a generally hydrogen-poor environment and chamber B has a generally hydrogen-rich environment. Chamber B may be physically separated from chamber A by a physical diffusion barrier **112**.

[0042] The non-limiting example electronics components **116** may be controls, central control units (CCU)s, power electronics, converters, inverters, switching devices, metal oxide semiconductor field effect transistor (MOSFET), insulated gate bipolar transistor (IGBT), thyristors or silicon controlled rectifiers (SCRs), switching regulators, capacitors, supercapacitors, the like, or a combination thereof.

[0043] The cell **100** further includes the cathode **108**, the anode **110**, the electrolyte **120**, HOR catalyst **122** on the anode side, and HER catalyst **124** on the cathode side.

[0044] The cell **100** includes a protective system **130** for the electronics components **116**. The protective system or assembly **130** includes one or more portions. The one or more portions of the protective system **130** may include a sorbent material **132**. The sorbent **132** may be arranged as one or more layers in chamber A **114** of the cell **100**. The sorbent **132** may be arranged adjacent to, directly adjacent to, or in direct contact with the electrolyte **120**, HOR catalyst **122** of the anode, or both. The sorbent **132** may form an intermediate layer between the electrolyte **120** and the HOR catalyst **122** of the anode. The sorbent **132** may have a greater or smaller thickness than the HOR catalyst **122**, the electrolyte **120**, or the HER catalyst **124**.

[0045] The sorbent **132** may be encapsulated in a containment, container, sub cell, case, sub chamber, encapsulation, or the like. The encapsulation **134** may be arranged adjacent to, directly adjacent to, or in direct contact with the sorbent **132**, the electrolyte **120**, the anode **110**, the HOR catalyst **122**, the diffusion barrier **112**, or a combination thereof. The contact between the encapsulation **134** and the sorbent **132**, the electrolyte **120**, the anode **110**, the HOR catalyst **122**, the diffusion barrier **112** may be partial or full. For example, as can be seen in FIG. 2A, the encapsulation **134** may have a partial contact with the diffusion barrier **112**. In contrast, FIG. 2B shows an extended direct contact between the encapsulation **134** and the diffusion barrier **112**. The encapsulation **134** may extend from a side of the cell **136** to the sorbent **132**. The diffusion barrier **112** may be in contact with the encapsulation **134** along its entire length. The encapsulation **134** may be made from a material that is selectively permeable to hydrogen to prevent contamination by other gases, for example contamination by any catalyst(s) used to aid the sorption kinetics. The cell **100** may thus include a stack of a cathode including the HER catalyst **124**, the electrolyte **120**, the sorbent **132**, the anode including the HOR catalyst **122**, and the encapsulation **134**.

[0046] The sorbent **132** may be mixed with a catalyst. For example, the sorbent **132** may be mixed with the HOR catalyst **122** to form a sorbent/anode/anode catalyst layer **138**, as is depicted in a non-limiting example of FIG. 2C.

[0047] The sorbent **132** may actively absorb hydrogen in chamber A **114** which contains the electronics components **116**. The sorbent **132** may have strong driving force for hydrogen uptake of at least about 5-20, 7-15, or 8-10 kJ/mol H<sub>2</sub>. The sorbent **132** may spontaneously take up hydrogen. The sorbent **132** may do so by sorption, chemisorption, physical adsorption, absorption, or a combination thereof. The sorbent may have a relatively high capacity to absorb/adsorb hydrogen. The absorption/adsorption of hydrogen within the sorbent **132** may proceed until a saturation point is reached. The saturation point of the sorbent **132** is a point at which the sorbent has no more capacity for additional hydrogen uptake.

[0048] The sorbent **132** may be rechargeable. The sorbent **132** may passively maintain the H<sub>2</sub>.

partial pressure until the sorbent **132** becomes saturated, at which point the sorbent **132** needs to be recharged. For the recharge purposes, the system **130** may include a recharge-enabling portion(s). The portions may include an electrical circuit **140**. The circuit may be external with respect to the system, cell, stack. The circuit may be internal with respect to the system, cell. The portions may be included in chamber A, B, or both. For example, chambers A and B may include an external circuit **140**. The circuit **140** may be connected to the cathode **108** and the sorbent **132**. The external circuit may be an electrochemical circuit **140** which may actively pull hydrogen from the sorbent **132** into chamber B **118**. The external circuit **140** may apply voltage bias during the recharge cycle to remove the adsorbed hydrogen.

[0049] The cell **100**, the system **130**, or both have three different states. The first or proton exchange state, the second or sorption state, and the third or regeneration state. In the first state, the system **130** functions as a typical electrochemical cell and is schematically depicted in FIG. **3**. The first state includes proton transport across the electrolyte **120**. In the first state, hydrogen leakage into chamber A **114** may occur. In the first state, the sorbent **132** is not saturated. In the first state, the sorbent **132** has capacity to take up, absorb, and/or adsorb hydrogen. In the first state, the sorbent **132** is not actively taking up hydrogen. Switch from the first state to the second state is activated when a predetermined maximum amount of hydrogen in chamber A **114** is reached and/or detected. The determination may be made, for example, by a controls unit **116** of the cell **100** based on one or more inputs from one or more sensors such as gas sensor(s) **142**.

[0050] The second or sorption state includes the sorbent **132** before the saturation point is reached. In the second state, the sorbent **132** is not saturated and has capacity to take up, absorb, and/or adsorb hydrogen. In the second state, proton transport across the electrolyte **120** is stopped. In the second state, hydrogen may enter the sorbent **132** material, and a reaction where hydrogen is split into H and ions may proceed. In the second state, spontaneous hydrogen adsorption maintains the hydrogen concentration in chamber A **114** below a predetermined concentration level. In the second state, hydrogen transport from chamber B **118** is being blocked by a voltage bias, electrolyte resistance, or both, as is discussed below.

[0051] The second state is schematically shown in FIG. **4**. The active sorbent material M spontaneously absorbs hydrogen to form a stable MH.sub.x material in the following reaction:



[0052] While the formation of MH.sub.x is thermodynamically favorable, the reaction may be catalyzed by the HOR catalyst **122**. In the second state, only H<sub>2</sub> from chamber A is being absorbed, and any H<sub>2</sub> from chamber B is being blocked by preventing any proton transport across the electrolyte.

[0053] Additionally, to counter the slow kinetics of hydrogen release, the reaction of the second state may be assisted by elevating the temperature of the system **130** by about 100 to 200° C. compared to initial temperature of the system **130**, cell **100** during the first state.

[0054] The excess H<sub>2</sub> diffusion from chamber B **118** may be prevented by one or more of the following strategies: (a) maintaining a bias voltage across the proton electrolyte **120** adjusted to be equal to the open circuit voltage so that the measured current across the external circuit **140** is zero, (b) disconnecting the external circuit **140** to block ion transport across the electrolyte **120**, (c) choosing an electrolyte **120** material with poor conductivity at ambient temperatures and good conductivity at elevated temperatures so that the proton transport across the electrolyte **120** is only appreciable when the temperature is artificially elevated, for example during the recharge cycle or the third state.

[0055] Switch from the second state to the first state is activated when a predetermined minimum amount of hydrogen in chamber A **114** is reached and/or detected. The determination may be made, for example, by a controls unit **116** of the cell **100** based on one or more inputs from one or more sensors such as gas sensor(s) **142**.



[0056] Switch from the second state to the third state is activated when a predetermined maximum amount of hydrogen in the sorbent **132** is reached and/or detected. The determination may be made, for example, by a controls unit **116** of the cell **100** based on one or more inputs from one or more sensors such as voltage sensor(s) **144**.

[0057] In the third state or regeneration, the sorbent **132** is being regenerated. The third state includes electrochemical regeneration of the sorbent **132** material. In the third state, hydrogen is driven out of the sorbent **132**, across the proton electrolyte **120**, and into chamber B **118** under an applied voltage bias. In the third state, the temperature of the cell **100**, sorbent **132**, or both may be increased to aid regeneration of the sorbent **132**. The temperature increase may be about 100 to 200° C. compared to initial temperature of the system **130**, cell **100**, or both during the first state, the second state, or both.

[0058] By applying a voltage bias across the proton electrolyte **120**, protons are removed from the active sorbent material **132** and moved to the HER catalyst **124** of the cathode. In the HER catalyst **124**, the protons are reduced to hydrogen gas. The third state is schematically shown in FIG. 5. The regeneration and desorption of the sorbent **132** is driven electrochemically in the following reaction:

$$\text{MH.sub.x.fwdarw.M+x/2H.sub.2} \quad (2).$$

[0059] Switch from the third state to the first state is activated when a predetermined minimum amount of hydrogen in the sorbent **132** is reached and/or detected. The determination may be made, for example, by a controls unit **116** of the cell **100** based on one or more inputs from one or more sensors such as voltage sensor(s) **144**.

[0060] The cell **100** and/or the system **130** may include one or more gas sensors **142** to determine the quantity or concentration of H.sub.2 present in the chamber A **114**. The one or more gas sensors **142** are schematically depicted in FIG. 2A. The one or more gas sensors **142** may be used to determine when the switch between states should happen. When the gas sensor(s) **142** indicate that a concentration of hydrogen in chamber A exceeded a predetermined maximum value, the cell's control system may initiate a switch from the first state to the second state. When the gas sensor(s) **142** indicate that a concentration of hydrogen in chamber A reached a predetermined minimum value, the cell's control system may initiate a switch from the second state to the first state. The gas sensor(s) **142** may be located in the vicinity of, adjacent to, directly adjacent to, or removed from the one or more electronic components **116**, the encapsulation **134**, the diffusion barrier **112**, or a combination thereof.

[0061] The cell **100** and/or the system **130** may include one or more voltage sensors **144** to determine the quantity or concentration of H.sub.2 present in the sorbent **132**. The voltage sensors **144** may measure the open-circuit voltage against a known reference (e.g. the cell stack) and thus measure the amount of H.sub.2 present in the sorbent **132**. The one or more voltage sensors **144** are schematically depicted in FIG. 2A. The one or more voltage sensors **144** may be used to determine when the switch between states should happen. When the voltage sensor(s) **144** indicate that a concentration of hydrogen in the sorbent **132** exceeded a predetermined maximum value, the cell's control system may initiate a switch from the second state to the third state. When the voltage sensor(s) **144** indicate that a concentration of hydrogen in the sorbent **132** was lowered by the regeneration to a predetermined minimum value, the cell's control system may initiate a switch from the third state to the first state. The voltage sensor(s) **144** may be located in the vicinity of, adjacent to, directly adjacent to, or within the sorbent **132**, the anode/sorbent mixed material **138**, the encapsulation **134**, the electrolyte **120**, the anode **110**, or a combination thereof.

[0062] The sensors **142**, **144** may be connected to a central processing unit (CPU), processing unit, memory, etc. that runs an algorithm to determine the conditions at which to activate the switch from the first to the second state, the second to the first state, the second to the third state, or the third to the first state.

[0063] The sorbent **132** may include one or more materials. The sorbent **132** may include one material or may be a mixture of materials. The material may have one or more of the following properties. The material may absorb hydrogen, adsorb hydrogen, or both. Sorption, adsorption, and absorption are used herein interchangeably, indicating that any sorption mechanism is applicable. The material may uptake hydrogen spontaneously. The material may be an active sorption material. The material may have a strong driving force for hydrogen absorption, good sorption kinetics at room temperature, substantial hydrogen storage capacity, allow for proton transport, or a combination thereof.

[0064] The material may include manganese dioxide (MnO<sub>2</sub>), gamma-MnO<sub>2</sub> often referred to as electrochemical manganese dioxide (EMD), nickel oxide hydroxide (NiOOH), or both. EMD and NiOOH may operate in the dry cell conditions and have capacity for a substantial amount of hydrogen uptake. Each material has its own advantage. EMD has twice the total hydrogen sorption capacity than NiOOH. NiOOH has a higher driving force for H<sub>2</sub> uptake. The hydrogen uptake may be realized via the following reactions:

$$\text{MnO}_2 + \text{H}_2 \rightarrow \text{Mn(OH)}_2 \quad (3) \text{ and}$$

$$\text{NiOOH} + \frac{1}{2}\text{H}_2 \rightarrow \text{Ni(OH)}_2 \quad (4).$$

[0065] The high driving force of both MnO<sub>2</sub> and NiOOH allow for a wide range of HOR **122** catalysts. The HOR catalyst **122** may be, for example, Pt, a Pt alloy such as Pt—Co or Pt—Ni, or Pd, AgO, Ag<sub>2</sub>O catalyst, the like, or a combination thereof.

[0066] The sorbent material may include only EMD or NiOOH. Alternatively, the sorbent material may include both EMD and NiOOH. For example, the sorbent **132** may include alternating layers of EMD and NiOOH. The layers may be positioned parallel or perpendicular to the electrolyte **120**. In another example, the sorbent **132** may include islands of EMD or NiOOH in a matrix of the alternate material.

[0067] The HER catalyst **124** may be, for example, Pt, a Pt alloy such as Pt—Co or Pt—Ni, Pd, or a phosphide such as CoP, MoP, FeP, MnP.

[0068] The proton electrolyte **120** may be chosen to be one of sulfonated tetrafluoroethylene-based fluoropolymer-copolymer, polybenzimidazole (PBI), or phosphate glass (e.g.

5P<sub>2</sub>O<sub>5</sub>·95SiO<sub>2</sub>). The conditions of the cell **100** and/or the system **130** may be adjusted based on the chosen materials. For example, if the electrolyte includes sulfonated tetrafluoroethylene-based fluoropolymer-copolymer, the operating conditions of the cell **100** should remain below about 100° C., and the electrolyte may be humidified in the recharge state. Proton transport through the sulfonated tetrafluoroethylene-based fluoropolymer-copolymer in the sorption state should be blocked electrochemically. If the electrolyte includes PBI, humidification may be optional, and the recharge state may proceed at temperatures as high as about 160° C. Proton transport during the sorption state should be blocked electrochemically. If the electrolyte includes phosphate glass, the recharge state may proceed at about 200° C., ensuring both good proton transport through the glass electrolyte, and good hydrogen removal kinetics from the active sorbent material.

[0069] The encapsulation **134** material may include a material which is selectively permeable to H<sub>2</sub>, but not to carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), or nitrogen dioxide (NO<sub>2</sub>). The encapsulation **134** material may be a polymer, thermoplastic, thermoset. A non-limiting example of the encapsulation material may be polymethyl methacrylate (PMMA) which is selectively permeable to H<sub>2</sub>, but not to CO, CO<sub>2</sub>, or NO<sub>2</sub>.

[0070] A method of utilizing system **100** is disclosed. The method may include running a chemical of electrochemical cell **100** in the first state. The method may include enabling, not blocking, proton transport across the electrolyte in the first state. The method may include measuring the amount of hydrogen seeping into a chamber A, where hydrogen presence is undesirable. The

method may include switching the system into the second state upon indication that a maximum predetermined concentration of hydrogen was measured/reached in the chamber A. The method may include adsorption of hydrogen from chamber A into the sorbent. The method may include preventing any proton transport from chamber B across the electrolyte in the second state. The method may include sorbing, adsorbing, absorbing hydrogen from chamber A **114** into the sorbent **132**. The method may include measuring the amount of hydrogen adsorbed into the sorbent in the second state. The method may include switching from the second state to the first state upon indication that a minimum predetermined amount of hydrogen was measured/reached in chamber A. The method may include switching from the second state to the third state upon indication that a maximum predetermined hydrogen concentration was measured/reached in the sorbent **132**. The method may include releasing hydrogen from the sorbent material. The method may include applying a voltage bias across the proton electrolyte **120** to remove hydrogen from the sorbent **132** to the HER catalyst **124** in chamber B **118**. The method may include reducing the hydrogen protons to hydrogen gas in the HER catalyst **124**. The method may include increasing temperature, pressure, or both to increase speed of the hydrogen release kinetics. The method may include preventing excess H<sub>2</sub> diffusion from chamber B **118** by one or more strategies (a)-(c) described above.

[0071] In one or more embodiments, an active hydrogen capture and release system **200** is disclosed. The system **200** may minimize hydrogen pressure buildup in a confined system of the chemical or electrochemical cell described above. The system **200** may be located in a chamber that is in close proximity to hydrogen rich areas such that there is physical separation of a hydrogen rich zone, chamber, or area **218**, where presence of hydrogen is desirable, and a zone, chamber, or area **214**, where presence of hydrogen is not desirable. The hydrogen poor or first zone **214** may have a target predetermined concentration of hydrogen c<sub>1</sub>. The hydrogen rich or second zone **218** may have a target predetermined concentration of hydrogen c<sub>2</sub>. c<sub>2</sub> is higher than c<sub>1</sub>. The system **200** may capture traces of leaked hydrogen in the zone **214** and/or from close proximity of electronics **216**.

[0072] The system **200** may be an active system. The system **200** may include an applied electric field, circuit, potential, voltage source **202** to modulate adsorption energy of hydrogen on an electrode **204**. The electric circuit may be internal or external to the system, to the cell. The active system **200** employs electrical bias to capture and release hydrogen gas. A non-limiting example of the system **200** is shown in FIGS. **6A** and **6B**. The system **200** may capture traces of leaked hydrogen.

[0073] FIG. **6A** shows a schematic of the system **200** and its components. The system **200** may include two electrodes separated by an air gap. The first electrode **204** may be an adsorbing electrode which may include a material structured to adsorb hydrogen. The second electrode **206** may be a counter electrode. The second electrode **206** may include material which is not structured to adsorb hydrogen. The system **200** may include a physical diffusion barrier layer **212** and one or more electronic components **216**, as described above.

[0074] The system **200** may include a hydrogen rich zone **218**, and a hydrogen free or hydrogen poor zone **214**. The zones **214** and **218** may be separated by the physical diffusion barrier layer **212**. Hydrogen may be seeping from the zone **218** to the zone **214** despite the barrier layer **212**, as is depicted in FIG. **6**.

[0075] Alternatively, as is shown in FIG. **6B**, the two electrode **204**, **206** may be separated by an H<sub>2</sub>-permeable solid dielectric **207** such as PMMA. The dielectric **207** may form a layer, barrier, or both. The dielectric **207** may be coated with a suitable catalyst to promote the dissociation of hydrogen gas into atomic hydrogen. Non-limiting examples of the catalyst may be Pt, Pd, or Ag.

[0076] The electrode **204** is formed at least partially, or entirely, from a material structured to adsorb hydrogen having adsorption capacity a<sub>1</sub>. The electrode **204** may also include a bulk portion

**210.** The bulk portion **210** may be made from a material which has a second adsorption capacity  $a_2$ .  $a_2$  is lower than  $a_1$  such that the bulk portion has a lower adsorption capacity than the adsorption material. Adsorption capacity or loading relates to the amount of adsorbate, in this case hydrogen, taken up by the adsorbent per unit mass of the adsorbent.

[0077] The adsorption material may be applied as a coating or top layer **208** on a bulk portion **210**, as is shown in FIG. **6A**. The coating or top layer may be continuous or discontinuous. The discontinuous top layer may appear as dispersed sites of the adsorbing material. Dispersion of the adsorption sites may form a pattern or be random. The discontinuous top layer may form one or more islands of adsorbing material on the surface of the bulk portion **210**.

[0078] The top layer **208** and the bulk portion **210** may have the same or different thicknesses.

[0079] Alternatively, as is shown in FIG. **6B**, the electrode's bulk portion **210** may be made from or include the adsorption material.

[0080] The adsorption material of the electrode **204** may provide adsorption surface/site to hydrogen. One or more portions of the electrode or electrode surface may act as adsorption sites to hydrogen. The one or more portions, or the entire surface of the electrode, may include the hydrogen adsorption sites. The one or more portions, adsorption sites may include material imperfections or defects such as vacancies, edges, etc. and/or doping sites including transition metal atoms, alkali metal atoms, etc. The electrode **204** may thus include a first surface with first enhanced value of hydrogen adsorption  $a_1$  and a second surface with lower adsorption capability  $a_2$ , the second value of hydrogen adsorption. The first value may be higher than the second value. The first surface may have one or more enhanced adsorption sites.

[0081] The material of the electrode may be, for example, a 2D form of carbon, graphene.

Electrode may be graphene-based. The electrode **204** may include doped or defected graphene. The FIGS. **7A-7C** depict examples of graphene structures which may be utilized as the electrode material in the system **200**. In other words, FIGS. **7A-7C** show non-limiting examples of doped graphene structures that may be effective in capturing hydrogen with the application of external electric field **202** of the system **200**. The black colored atoms represent doping, white atoms represent hydrogen. FIG. **7A** shows a defective graphene sheet with two-five carbon rings locked to two-seven carbon rings (5.sup.27.sup.2) doped with atom M (black). In FIG. **7B**, defective graphene sheet is depicted. The defective graphene sheet includes two-five carbon rings connected to an eight carbon ring (5.sup.28) doped with atom M (black). M may be, for example, Pt, Ni, Pd, or Li. FIG. **7C** shows doped graphene sheet with nitrogen (black).

[0082] When doped, defective graphene can be an efficient route for hydrogen capture. Hydrogen adsorbs to a doping atom M in 5.sup.27.sup.2 defect, where atom M is located on a bridge site (FIG. **7A**) or in 5.sup.28 defect, where atom M is located in octatomic ring (FIG. **7B**).

[0083] Atom M may be a transition metal or an element in the d-block of the Periodic Table of elements, which includes group IIIB to XIIB on the periodic table. Atom M may be Ni, Co, Pd, Pt, Fe, Ru, Co, Rh, Ir, Ni, Pd, Pt, Cu, Ag, or Au. Alternatively, atom M may be an alkali metal or an element from group IA of the Periodic Table. Atom M may be Li, Na, K, or Rb.

[0084] The system **200** functions as an active hydrogen pump structured to capture and release hydrogen gas. The system **200** works by applying electric field normal to the graphene plane, which significantly enhances adsorption of hydrogen. Specifically, the application of external electric field reduces the barrier for hydrogen chemisorption by polarizing the H<sub>2</sub> molecule and activate the electrode adsorption material to capture hydrogen. Additionally, the applied field promotes dopant dispersion and minimizes clustering, which enhances the gravimetric capacity or the amount of H<sub>2</sub> adsorbed per unit mass of the system **200**. Applying electric field pointing away from the graphene plane causes an increase in binding energy, while flipping the field direction causes reduction in binding energy, allowing the release of hydrogen. The field reversal may be implemented by a positive or negative voltage bias on the electrode. The counter electrode **206** acts as ground.

[0085] The applied field increases hydrogen adsorption energy of the adsorption sites of the electrode **204**, effectively trapping floating hydrogen molecules in the material of the electrode **204**, and reducing hydrogen concentration and buildup near the digital components **216** in the system **200**. The adsorption sites are thus activatable by the application of the electric field as described above.

[0086] Further still, another form of doping considers the addition of nitrogen (FIG. 7C). When nitrogen is present, no defect is needed to be present in the graphene sheet where N is embedded. Additionally, nitrogen doping often does create associated defects near the doping site. The application of external field, described above, promotes the transition of hydrogen molecule to split near the nitrogen atom and get adsorbed in its atomic form to the adsorption site(s) in the graphene sheet.

[0087] The system **200** has a first or capture mode or cycle and a second or release mode or cycle. In the capture mode, the external electric field normal or specific voltage is applied to the electrode **204**. In the capture mode, the external electric field normal or specific voltage is applied to reduce the barrier for hydrogen chemisorption by polarizing the H<sub>2</sub> molecule. If the electrode **204** contains vacancies or doping, as was described above, adsorption of hydrogen by the adsorption sites on the electrode **204** is enhanced, and hydrogen is being captured or trapped in the adsorption sites of the material. If the electrode **204** includes nitrogen, hydrogen molecules split near the nitrogen atom and get absorbed in the atomic form to the adsorption site(s) in the electrode material.

[0088] In the release mode, a change in the electric field is made to allow the electrode **204** to reset, and the captured or trapped hydrogen is safely ejected out of the system **200** into the surrounding environment. The desorption of hydrogen may be facilitated by reversing the field direction and/or switching the electrical circuit **202** off. Switching off the applied voltage or reversing the field direction releases the adsorbed hydrogen due to the significant reduction in the adsorption energy. To avoid kinetic barriers of hydrogen release, the polarity of the electrode **204** may be reversed. At the end of the release mode, the electrode's adsorption sites are emptied or cleared and ready to capture more hydrogen.

[0089] To refresh the electrode **204** during desorption, the hydrogen is removed from the system **200**. The hydrogen removal may be conducted by several different ways. For example, the electrode **204** may be a removable and replaceable component of the system **200**. Hence, when the electrode's adsorption sites are filled to a predetermined level, the electrode **204** may be removed from the system **200** and a new electrode **204** installed.

[0090] Alternatively, the system **200** may be placed in an environment that will remove hydrogen into the environment during the desorption cycle. Such environment may be a high temperature or low pressure external environment.

[0091] Alternatively still, the system **200** may include one or more types of additives that create an oxidizing environment such as OH radicals or peroxides, Pt-wire or other catalysts, or the like, that can oxidize the hydrogen into water.

[0092] Further, the system **200** may receive or be exposed to an item acting as “hydrogen getter” during the desorption cycle such that undesirable captured hydrogen is forced to leave the system **200**. A non-limiting example of the “hydrogen getter” may be transition-metals or transition-metal oxides, especially those involving rare earth elements such as Ce and/or La.

[0093] Similarly to the system **100**, the system **200** may include gas and/or voltage sensors **242**, **244** monitoring concentration of hydrogen in the system. For example, the system **200** may include a gas or voltage sensor **242**, **244** near, adjacent to, or directly adjacent to the one or more electric components **216**, the electrode **204**, the like, or a combination thereof.

[0094] A method of using the system **200** is disclosed. The method may include utilizing an electrical circuit and hydrogen adsorption material to capture and release hydrogen atoms to reduce hydrogen concentration near one or more digital components of the system. The method may

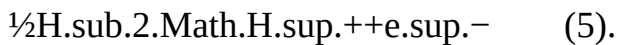
include measuring, detecting, monitoring, maintaining concentration of hydrogen in the system, cell, pump, near, adjacent to, directly adjacent to the electrode **204**, the electrode **206**, the one or more electric components **216**. The method may include adjusting, lowering concentration of hydrogen the system, cell, pump, near, adjacent to, directly adjacent to the electrode **204**, the electrode **206**, the one or more electric components **216**.

[0095] The method may include increasing hydrogen adsorption capacity of one or more adsorbing sites on an adsorbing electrode. The increasing may include applying electric field normal to a plane of the adsorbing electrode. The method may include capturing hydrogen by the one or more adsorbing site of the adsorbing electrode. The method may include polarizing hydrogen molecules present in the system by the electrical circuit. The method may include utilizing defective material such as including vacancies, doping element, etc. as the adsorption sites.

[0096] The method may include releasing the captured hydrogen from the one or more adsorbing sites, the electrode, the system, or a combination thereof. The method may include utilizing the electrical circuit to release the captured hydrogen. The decreasing may include reducing the hydrogen adsorption capacity of the one or more adsorbing sites. The reducing may include causing a change in the electric field. The reducing may include the field reversal. The reducing may include switching the field off.

[0097] In one or more embodiments, a chemical or electrochemical system **300** is disclosed. The system **300** includes a hydrogen pump component **303** configured to protect electrical components **316**, present in the system **300**, from exposure to high concentrations of H.sub.2 gas. The pump **303** may supplement or replace a physical diffusion barrier **312** to maintain the H.sub.2 concentration in the vicinity of the control circuitry and/or other digital components **316** below a pre-defined level.

[0098] A non-limiting example of the system **300** is shown in FIG. **8**. The system **300** may include an electrochemical cell **300**, where hydrogen in transport is controlled by a voltage bias between two electrodes **345**, **346**. The system/pump **300/303** may include a symmetrical electrochemical cell, where both cathode **346** and anode **345** perform the hydrogen redox reaction:



[0099] The net reaction is then:

$\text{H.sub.2.sup.(A).fwdarw.H.sub.2.sup.(B)}$  (6), [0100] where H.sub.2.sup.(A) and H.sub.2.sup.(B) refer to hydrogen gas in the hydrogen rich and hydrogen poor zones **318**, **314**.

[0101] The free energy of reaction (6) is defined by the concentrations of H.sub.2 in chambers **314** and **318** and the voltage applied across the external circuit:

$\Delta G = RT \ln(p.\text{sub.B}/p.\text{sub.A}) - FV$  (7), [0102] where [0103] p.sub.A and p.sub.B are the partial pressures of H.sub.2 in chambers **314** and **318**, [0104] R is the ideal gas constant, [0105] T is the temperature in Kelvin, [0106] F is the Faraday constant, and [0107] V is the voltage bias across the external circuit.

[0108] At equilibrium, where  $\Delta G = 0$ , the applied voltage bias thus sets the ratio of partial pressures of hydrogen in chambers **314** and **318**. Given that the partial pressure in chamber **318** is a known controlled quantity, the voltage bias can then be set to maintain the H.sub.2 level in chamber **314** at a pre-defined level. The open-circuit voltage may be used to measure the H.sub.2 concentration in chamber **314** relative to that of chamber **318**.

[0109] The electrodes **345**, **346** are separated by a proton-conductive electrolyte **348** and an external circuit **340**. The electrodes are a cathode **346** in the hydrogen rich portion of the system **318** and an anode **345** in the hydrogen poor or hydrogen free portion of the system **314**.

[0110] The pump **303** may be an active electrochemical pump. The pump **303** is configured to maintain the H.sub.2 concentration near one or more control electronics **316** below a pre-defined

level. The system **300** utilizes voltage to conduct hydrogen from one zone **314** to the other **318**. As such, the system **300** requires constant voltage to operate. The system **300** may be a constantly running or continuously running system. The system **300** may be free of a hydrogen sorbent material. The system **300** may include a sorbent. The sorbent may be a sorbent described above with respect to the system **100**, **200**, or both. The pump **303** may be located adjacent or directly adjacent to the high-hydrogen cathode.

[0111] The pump **303** operates by applying a voltage across the external circuit **340** to drive proton transport across the electrolyte **348** from one electrode to the other. By applying an appropriate bias, H.sub.2 that diffuses across the physical diffusion barrier may thereby be pumped out of the chamber or zone **314** containing the H.sub.2-sensitive control electronics **316**.

[0112] As is shown in FIG. **8**, the pump **303** may be integrated into the hydrogen diffusion barrier **312**. The pump may include a stack of cathode **346** and anode **345** components. Specifically, the pump **303** may include a cathode gas diffusion layer (GDL) **350**, cathode catalyst **352**, electrolyte **348**, anode catalyst **354**, anode GDL **356**, and anode encapsulation **358**. The anode encapsulation **358** may serve the same purpose as the encapsulation **134**, described herein. The encapsulation **358** may be selectively permeable to H.sub.2, but not to CO.sub.2, CO, and NO.sub.2, which may poison the anode catalyst.

[0113] The external circuit **340** connecting the anode **345** and cathode **346** is biased to drive H.sup.+ current from the anode **345** to the cathode **346**, thereby pumping any H.sub.2 that diffused into H.sub.2-poor chamber **314** across the H.sub.2 diffusion barrier **312** back into the H.sub.2 rich chamber **318**.

[0114] To ensure that the H.sub.2 pump **303** is able to operate close to thermodynamic equilibrium, at least some of following conditions may need to be met: [0115] (I) The cathode catalyst **352** is able to perform the hydrogen evolution reaction (HER:  $\text{H}^+ + \text{e}^- \rightarrow \frac{1}{2}\text{H}_2$ ) with minimum overpotential. [0116] (II) The cathode GDL **350** can provide sufficient transport to the produced H.sub.2 gas to ensure that the H.sub.2 partial pressure at the cathode **346** is the same as that in the chamber or zone **318**. [0117] (III) The electrolyte **348** provides sufficient conductivity for H.sup.+ to minimize Ohmic losses while blocking any electrical currents. [0118] (IV) The anode catalyst **354** is able to perform the hydrogen oxidation reaction (HOR:  $\frac{1}{2}\text{H}_2 \rightarrow \text{H}^+ + \text{e}^-$ ) with minimum overpotential. [0119] (V) The anode GDL **356** can provide sufficient transport to H.sub.2 gas to ensure that the H.sub.2 partial pressure at the anode **345** is the same as that in chamber **314**. [0120] (VI) All components of the system **300** and/or the pump **303** remain stable at the operating conditions of the pump **303**. Specifically, the catalysts **352**, **354** are not poisoned by other gases (air, CO, CO.sub.2) present in chambers **314**, **318**. To protect the cathode catalyst **352**, anode catalyst **354**, or both, the anode **345** may be encapsulated in a material selectively permeable to H.sub.2, but not to CO, CO.sub.2, and/or NO.sub.2. A non-limiting example of such a material may be PMMA.

[0121] Non-limiting examples of the anode catalyst **354** may be Pt, a Pt-alloy such as Pt—Co or Pt—Ni or Pd.

[0122] The cathode catalyst **352** may be Pt, a Pt-alloy or Pd, or a metal phosphide such as CoP, MoP, FeP, or MnP. The cathode and anode GDLs **350**, **356** may include porous carbon, analogous to those used in polymer electrolyte membrane fuel cells (PEMFC). The electrolyte **348** may be made from a material mentioned above. Other materials are contemplated for all the components.

[0123] Just like the system **100** described above, the system **300** may include one or more gas or voltage sensors **342**, **344** to determine the quantity or concentration of H.sub.2 present in the chamber A **314**. The gas, voltage sensor(s) **342**, **344** may be equivalent to gas, voltage sensor(s) **142**, **144** described above. The one or more gas, voltage sensor **342**, **344** may be connected to a CPU, processing unit, memory, etc. that runs an algorithm to determine the hydrogen concentration at which to activate the pump **303**.

[0124] The system **300**, pump **303**, or cell, may include a controller. The controller may be present

in the hydrogen poor zone, chamber, or area **314**. The controller may be the electronic digital component **316**. The controller may operate the pump **303** based on one or more inputs. The one or more inputs may include concentration of hydrogen in the hydrogen rich zone, concentration of hydrogen in the hydrogen poor zone, predetermined concentration of hydrogen in the cell, zone **314**, zone **318**, partial pressure in the hydrogen rich zone, partial pressure in the hydrogen poor zone, temperature in the hydrogen rich zone, temperature in the hydrogen poor zone, ratio of partial pressure in the hydrogen poor zone and hydrogen rich zone, or a combination thereof. The controller may generate one or more outputs such as value of voltage bias to be set/applied to maintain the H.sub.2 level the hydrogen poor zone at the pre-defined level. The controller may generate input based on the formula (7). The controller may operate the pump close to thermodynamic equilibrium. The controller may collect input regarding conditions (I) to (VI). If the conditions are met, the controller may operate the pump. If the conditions are not met, the controller may stop operating the pump. The controller may initiate correction within the system such that the conditions (I) to (VI) are met while the pump is operating.

[0125] A method of utilizing the pump of the system **300** is disclosed. The method may include one or more of the following tasks performed, directed, or controlled by a controller. The method may include operating a hydrogen pump of the system **300** to maintain the H.sub.2 concentration in the vicinity of the control circuitry and/or other digital components **316** below a pre-defined level. The method may include controlling hydrogen transport in the system **300** by a voltage bias between the two electrodes **345**, **346**. The method may include utilizing voltage to conduct hydrogen from one zone **314** to the other **318**. The method may include applying a voltage across the external circuit **340** to drive proton transport across the electrolyte **348** from one electrode to the other. The method may include pumping H.sub.2 which diffuses across the physical diffusion barrier from the hydrogen rich zone to the hydrogen poor zone, back to the hydrogen rich zone.

[0126] The method may include setting the voltage bias to maintain the H.sub.2 level in chamber **314** at a pre-defined level based on the partial pressure value in the hydrogen rich zone. The method may include determining the partial pressure value in the hydrogen rich zone. The method may include measuring H.sub.2 concentration in the hydrogen poor zone relative to that of the hydrogen rich zone based on the open-circuit voltage.

[0127] The method may include operating the pump continuously. The method may include operating the pump close to thermodynamic equilibrium. The method may include measuring hydrogen concentration in the system. The method may include measuring voltage within the system. The method may include checking, ensuring if the conditions (I) to (VI) are met. The method may include making adjustments to the system to ensure that the conditions (I) to (VI) are met.

[0128] While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms encompassed by the claims. The words used in the specification are words of description rather than limitation, and it is understood that various changes can be made without departing from the spirit and scope of the disclosure. As previously described, the features of various embodiments can be combined to form further embodiments of the invention that may not be explicitly described or illustrated. While various embodiments could have been described as providing advantages or being preferred over other embodiments or prior art implementations with respect to one or more desired characteristics, those of ordinary skill in the art recognize that one or more features or characteristics can be compromised to achieve desired overall system attributes, which depend on the specific application and implementation. These attributes can include, but are not limited to cost, strength, durability, life cycle cost, marketability, appearance, packaging, size, serviceability, weight, manufacturability, ease of assembly, etc. As such, to the extent any embodiments are described as less desirable than other embodiments or prior art implementations with respect to one or more characteristics, these



embodiments are not outside the scope of the disclosure and can be desirable for particular applications.

## Claims

1. A hydrogen electrochemical cell comprising: a first hydrogen-rich zone including a cathode, a second hydrogen-poor zone including an anode, a controls electronic component configured to switch the cell between a first mode that allows proton transport from the cathode to the anode and a second mode that interrupts proton transport and allows the sorbent to capture hydrogen, and a sorbent configured to capture hydrogen in the second zone and release hydrogen protons into the first zone, the sorbent being encapsulated in a material selectively permeable to hydrogen and impermeable to carbon monoxide, carbon dioxide, and nitrogen dioxide, an electrolyte located between the cathode and the sorbent, and an electrical circuit arranged to apply voltage bias to remove the captured hydrogen from the sorbent.
2. The electrochemical cell of claim 1 further comprising a physical diffusion barrier structured to minimize influx of hydrogen from the first zone to the second zone.
3. The electrochemical cell of claim 1, wherein the sorbent, being a separate component from the anode, and the anode are encapsulated in the material selectively permeable to hydrogen and impermeable to carbon monoxide, carbon dioxide, and nitrogen dioxide.
4. The electrochemical cell of claim 1, wherein the first hydrogen-rich zone further includes a catalyst configured to reduce the released hydrogen to hydrogen gas.
5. The electrochemical cell of claim 1 further including a gas sensor structured to measure concentration of hydrogen in the second hydrogen-poor zone.
6. The electrochemical cell of claim 1 further including a voltage sensor structured to measure concentration of hydrogen in the sorbent.
7. The electrochemical cell of claim 1, wherein the sorbent is rechargeable.
8. A hydrogen electrochemical system comprising: a cathode side; an electrolyte disposed between the cathode side and an anode side; and the anode side having an anode encapsulated in a material to be free of direct contact with the electrolyte, a hydrogen sorbent layer sandwiched between the electrolyte and the anode, and a controls electronics component configured to switch from a first state to a second state when a hydrogen concentration at the anode exceeds a first threshold, switch from the second state to a third state when a hydrogen concentration in the sorbent exceeds a second threshold, switch from the second state to the first state when the hydrogen concentration at the anode falls below a third threshold, and switch from the third state to the first state when the hydrogen concentration in the sorbent falls below a fourth threshold, the hydrogen electrochemical system having the first state of proton transport from the cathode side to the anode side across the electrolyte, the second state of adsorbing hydrogen into the hydrogen sorbent layer from the anode side while interrupting proton transport across the electrolyte, and the third state of electrochemical regeneration of the hydrogen sorbent layer by hydrogen removal from the hydrogen sorbent layer across the electrolyte onto the cathode side under an applied voltage bias.
9. The electrochemical system of claim 8, wherein the proton transport is interrupted in the second state by electrolyte resistance.
10. The electrochemical system of claim 8, wherein the proton transport is interrupted in the second state by maintaining a bias voltage across the electrolyte.
11. The electrochemical system of claim 8, wherein the sorbent is not adsorbing hydrogen in the first state.
12. The electrochemical system of claim 8, wherein the system is configured to switch from the first state to the second state when a predetermined maximum amount of hydrogen is detected on the anode side.
13. The electrochemical system of claim 8, wherein the system is configured to switch from the

second state to the third state when a predetermined maximum amount of hydrogen in the sorbent is detected.

**14.** The electrochemical system of claim 8, wherein the system is configured to switch from the second state to the first state when a predetermined minimum amount of hydrogen is detected on the anode side.

**15.** The electrochemical system of claim 8, wherein the system is configured to switch from the third state to the first state when a predetermined minimum amount of hydrogen is detected in the sorbent.

**16.** A hydrogen electrochemical cell comprising: a stack including a cathode, an electrolyte directly adjacent to the cathode, an anode, and a hydrogen sorbent material adjacent to the electrolyte, the hydrogen sorbent forming a discrete layer adjacent the anode, the sorbent material encapsulated in a first encapsulation material selectively permeable to hydrogen, the stack at least partially surrounded by an encapsulation material selectively permeable to hydrogen such that the sorbent material and the anode are at least partially surrounded by the encapsulation material, and a digital component adjacent to the stack, the digital component comprising a processor configured to control switching of the cell between a hydrogen capture mode and a proton transport mode based on detected hydrogen concentrations.

**17.** The electrochemical cell of claim 16, wherein the digital component includes a central processing unit.

**18.** The electrochemical cell of claim 16, wherein the hydrogen sorbent material and a catalyst form a mixed material.

**19.** The electrochemical cell of claim 16, wherein the stack is connected to an external electrical circuit at the sorbent and at the cathode.

**20.** The electrochemical cell of claim 16, wherein the stack is attached to a physical diffusion barrier structured to minimize influx of hydrogen from the cathode to the anode.

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