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(54) **POROUS LAYERS WITHIN
ELECTROCHEMICAL CELLS HAVING
DIRECTIONALLY ORIENTED CHANNELS**

(52) **U.S. Cl.**
CPC *C25B 13/02* (2013.01); *C25B 13/05*
(2021.01)

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(57) **ABSTRACT**

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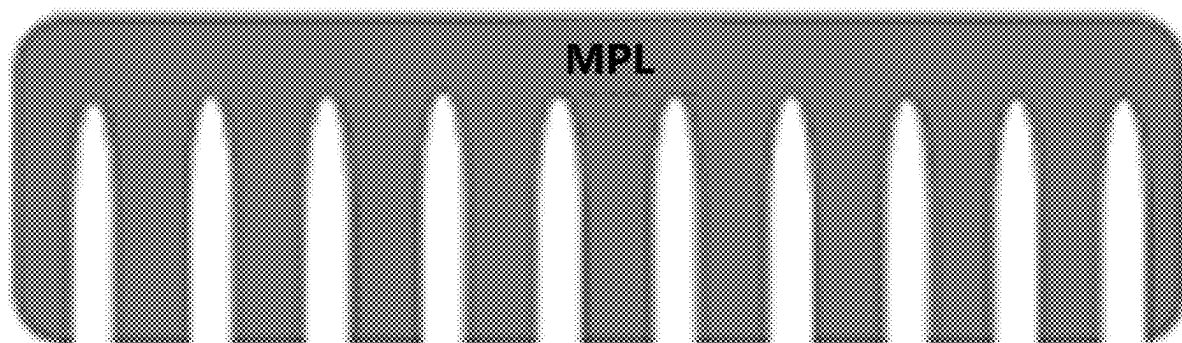
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21, 2024.

Publication Classification

(51) **Int. Cl.**
C25B 13/02 (2006.01)
C25B 13/05 (2021.01)

The following disclosure relates to electrochemical or electrolysis cells and components thereof. More specifically, the following disclosure relates to porous layers and methods of making such porous layers for electrochemical cells. In certain examples, the porous layer includes a plurality of channels that extend through at least 50% of a depth of the porous layer as measured in a direction perpendicular to a plane in which the porous layer is oriented, wherein the porous layer is configured to convey a two-phase mixture of liquid and gas within the electrochemical cell, and wherein each channel of the plurality of channels is configured to facilitate a transfer of gas from the porous layer into an adjacent flow field of the electrochemical cell.



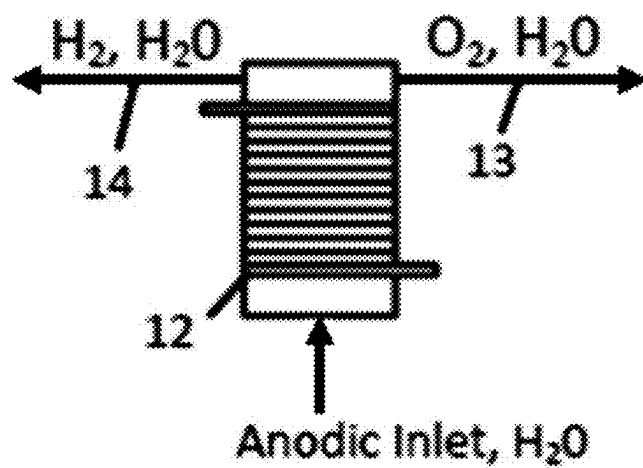


FIGURE 1

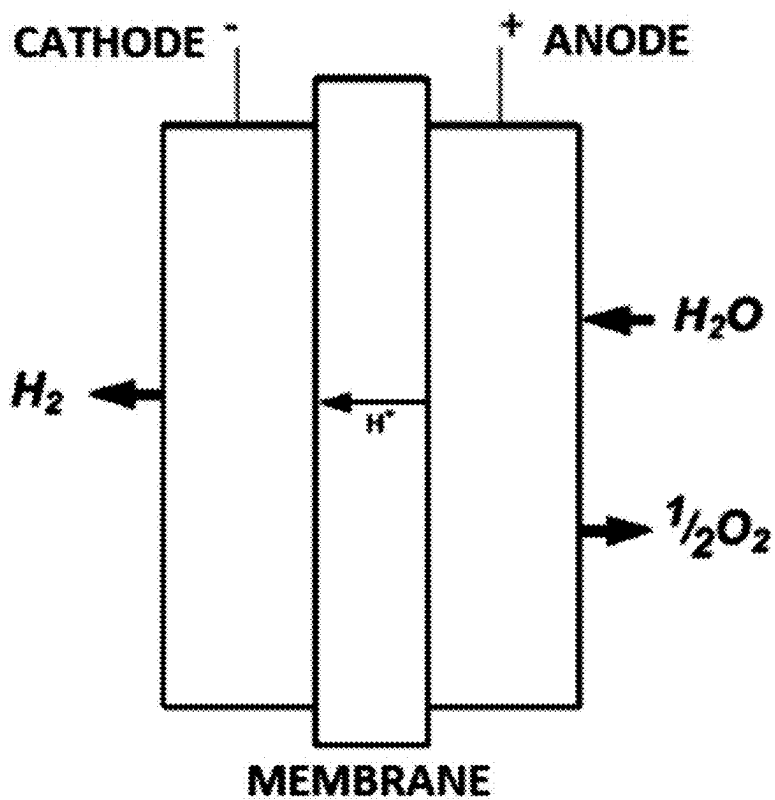


FIGURE 2

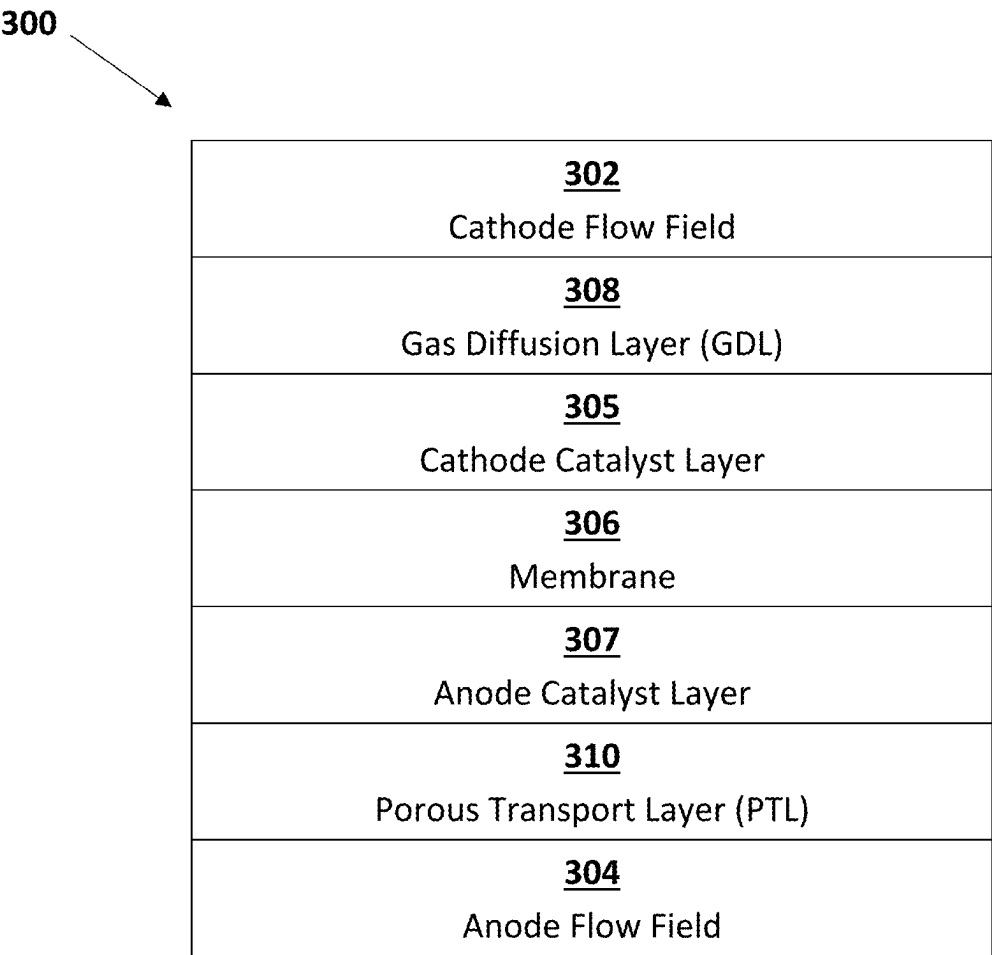


FIGURE 3

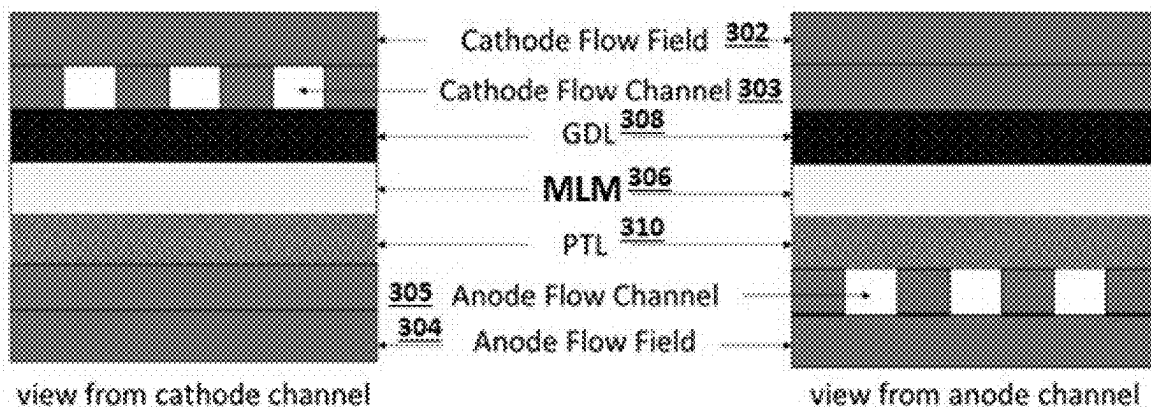


FIGURE 4A

FIGURE 4B

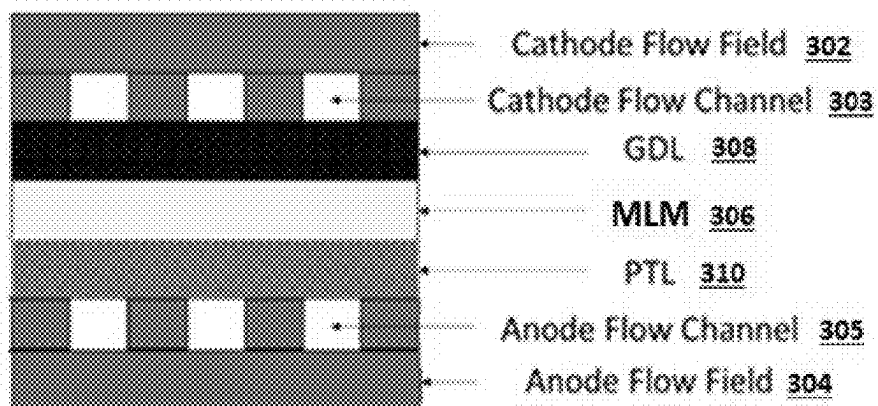


FIGURE 4C

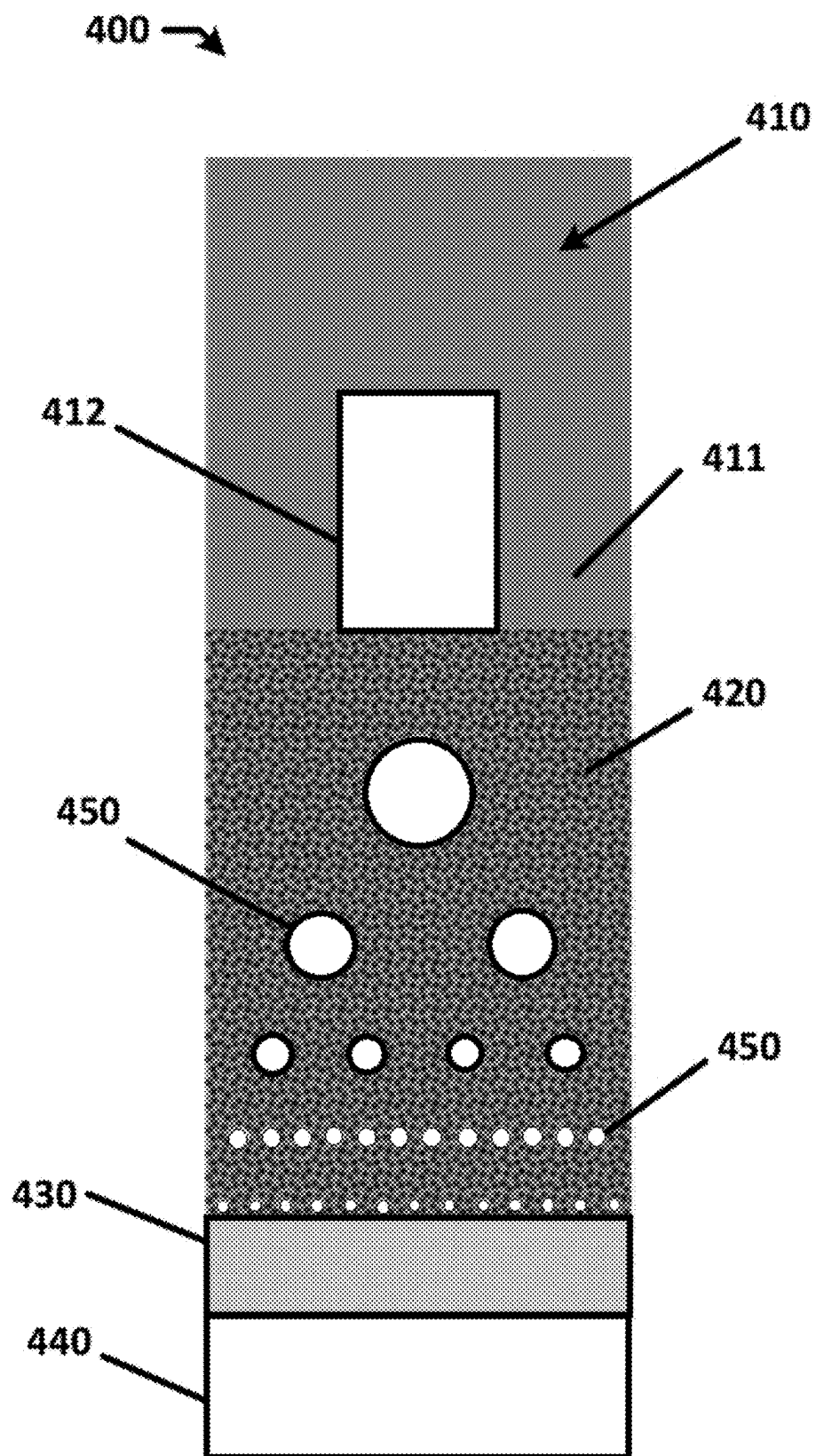


FIGURE 5

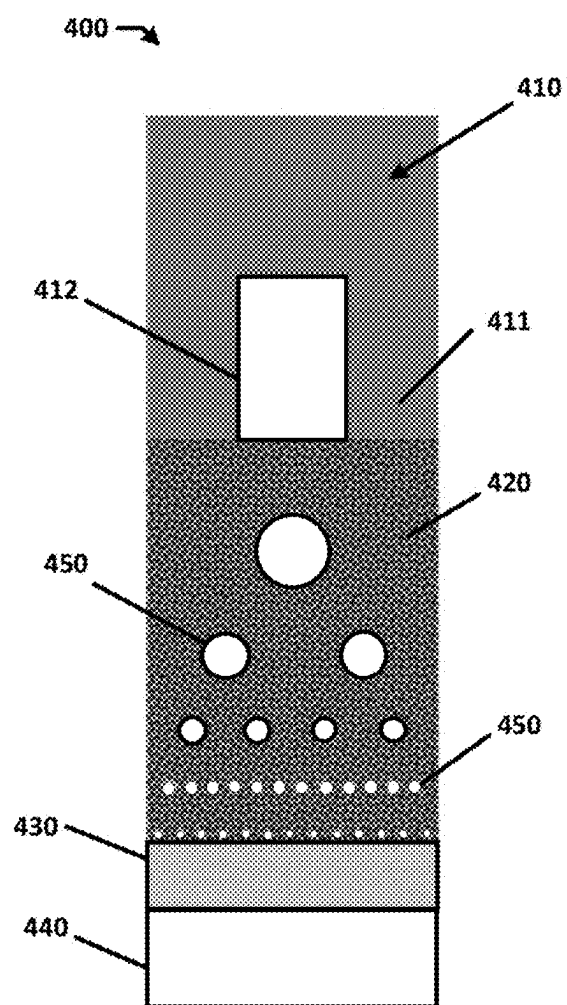


FIGURE 6A

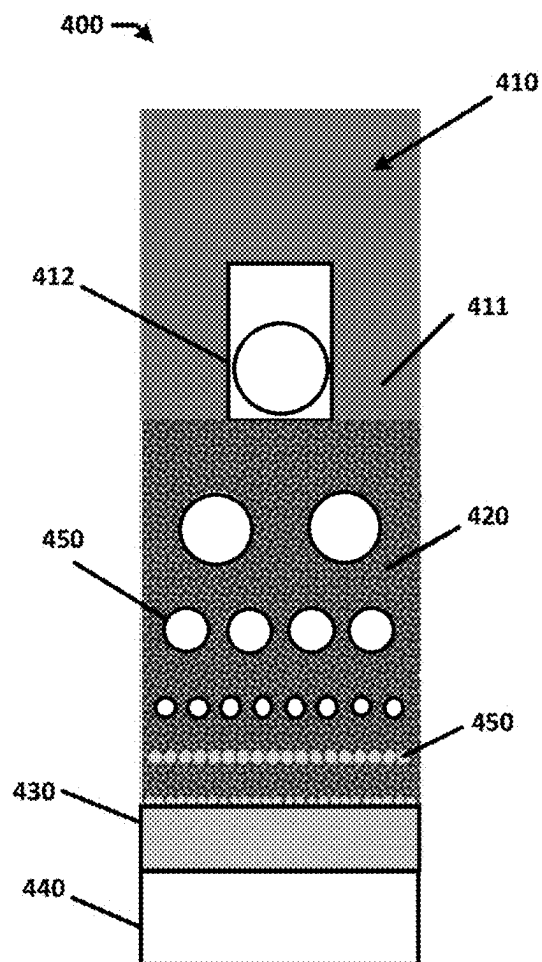


FIGURE 6B

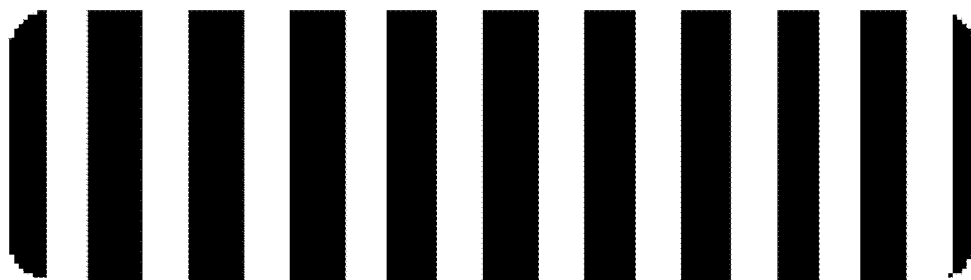


FIGURE 7A

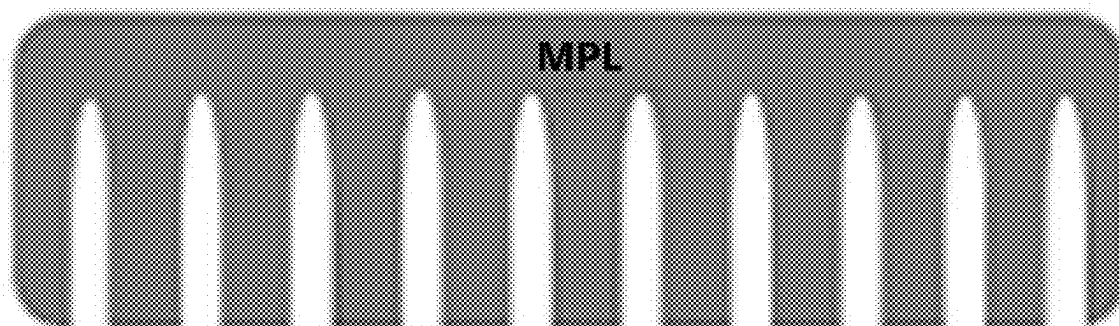


FIGURE 7B

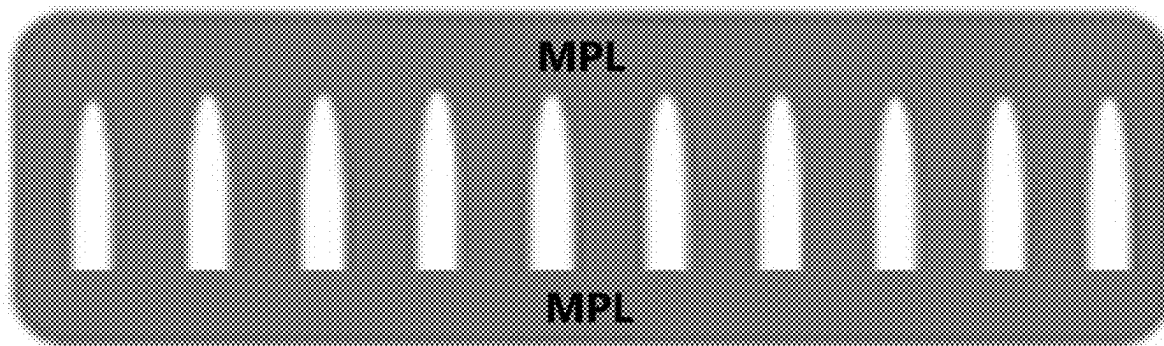


FIGURE 7C

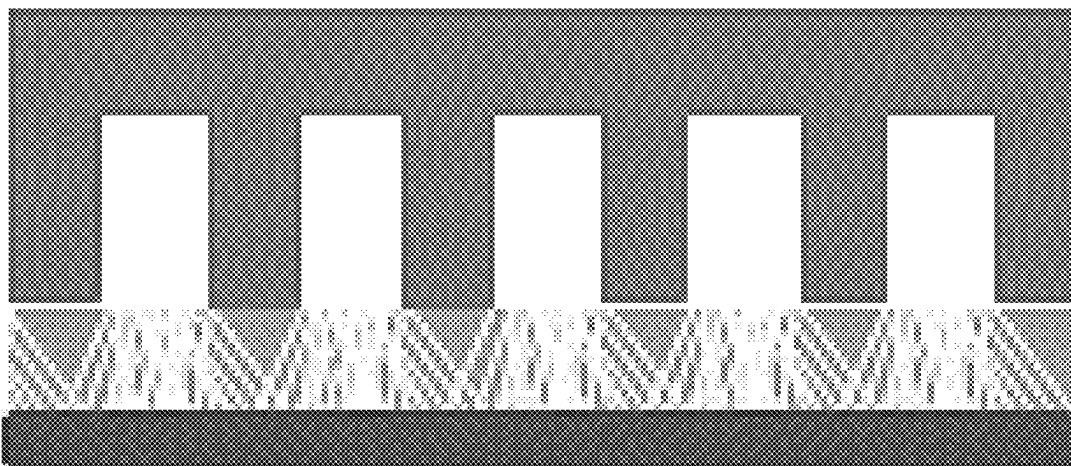


FIGURE 7D

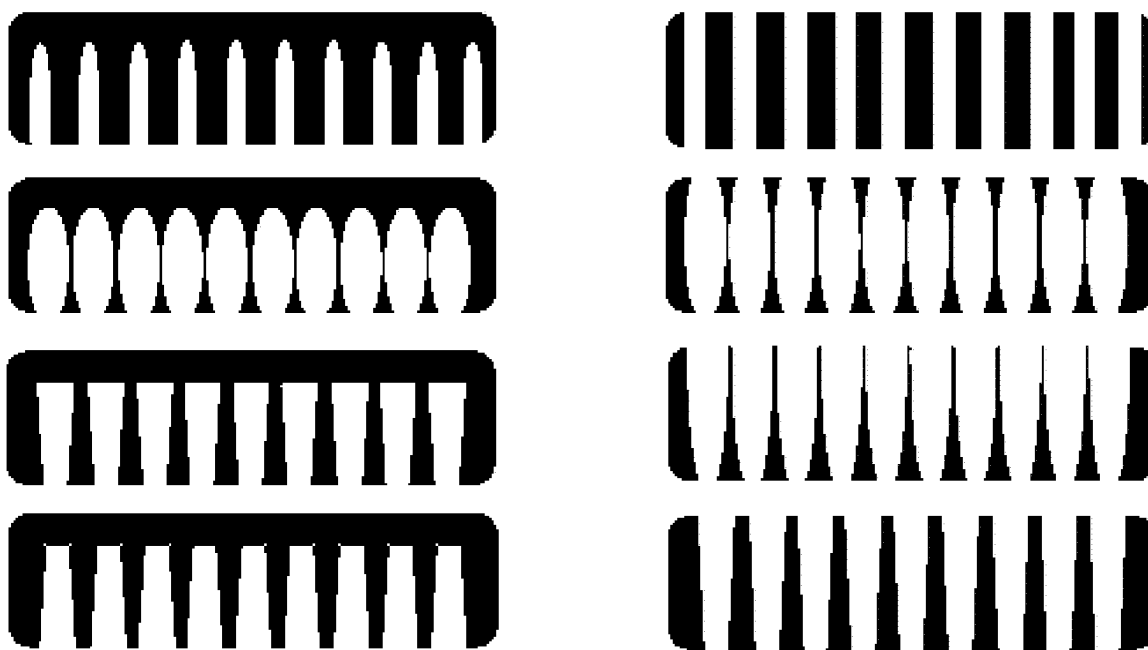


FIGURE 8

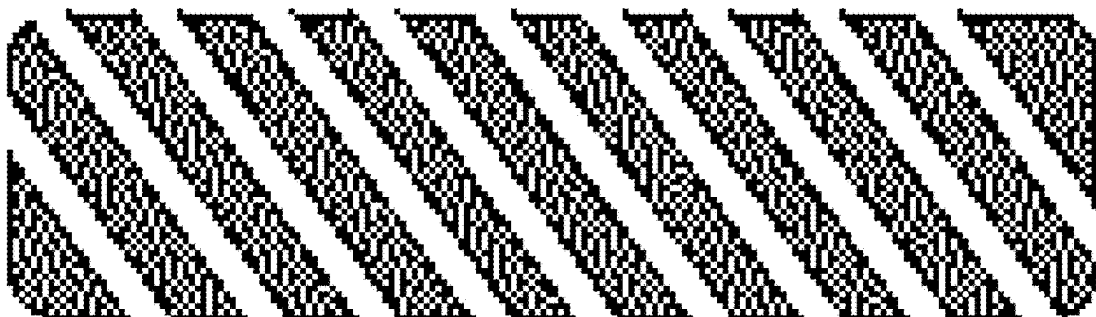


FIGURE 9A

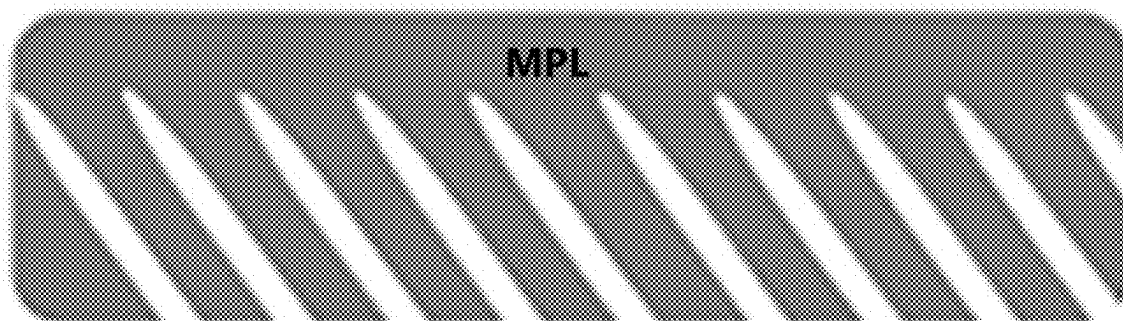


FIGURE 9B

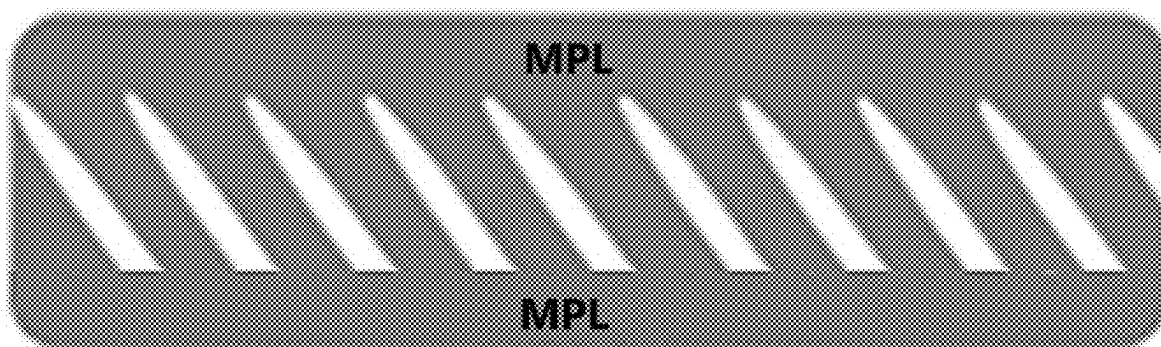


FIGURE 9C

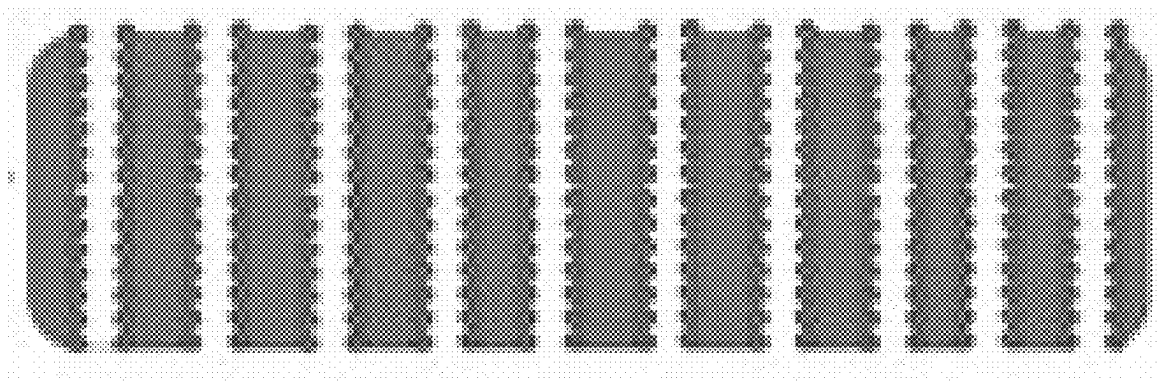


FIGURE 10A

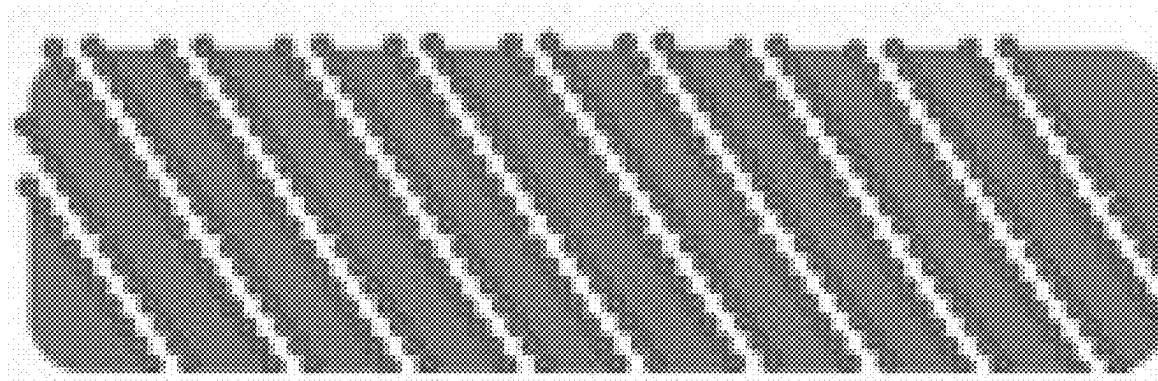


FIGURE 10B

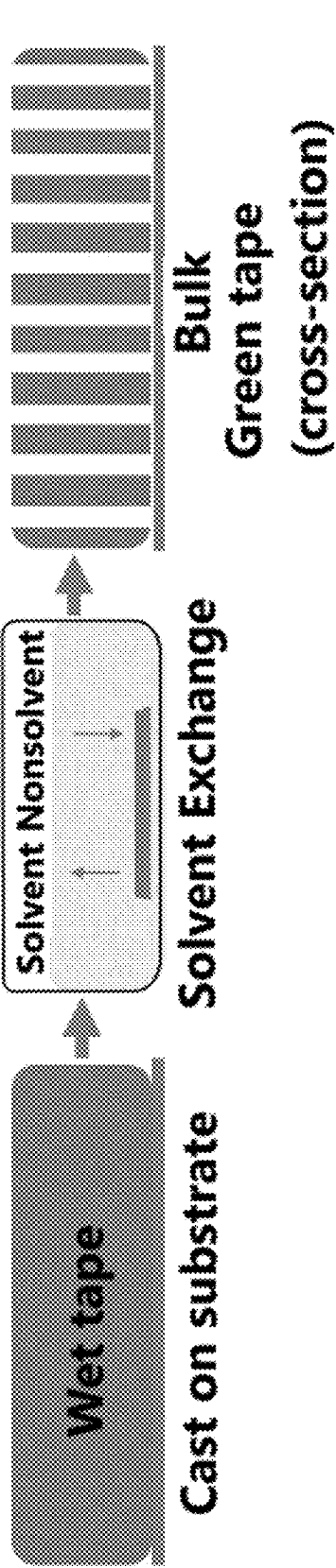


FIGURE 11

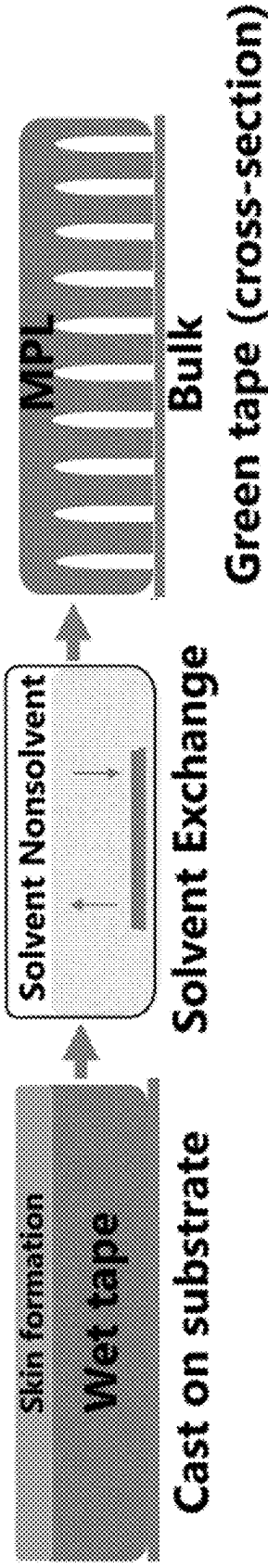


FIGURE 12A

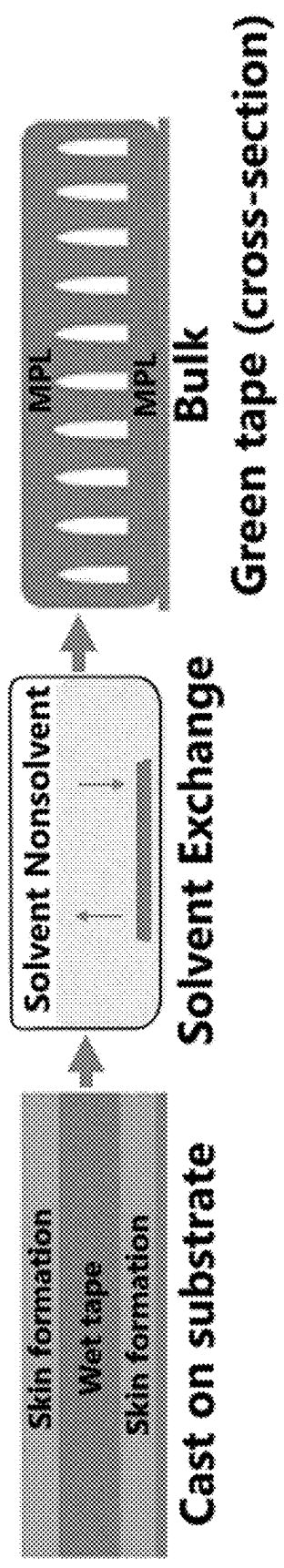


FIGURE 12B

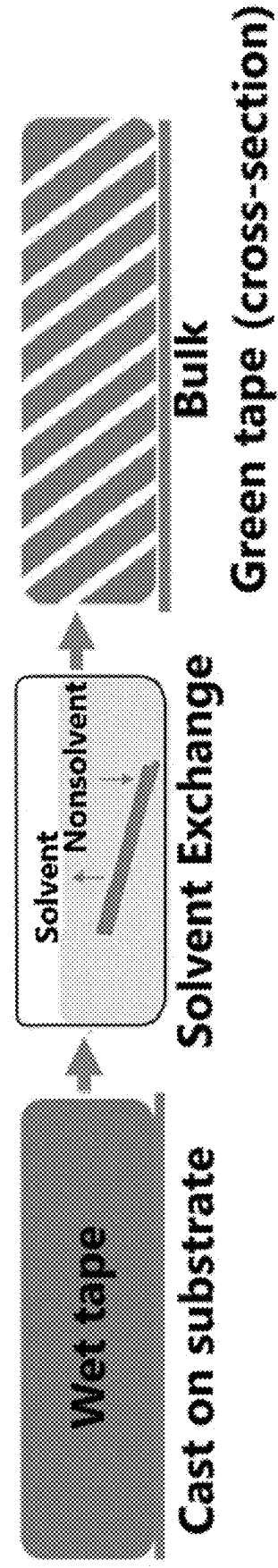


FIGURE 13

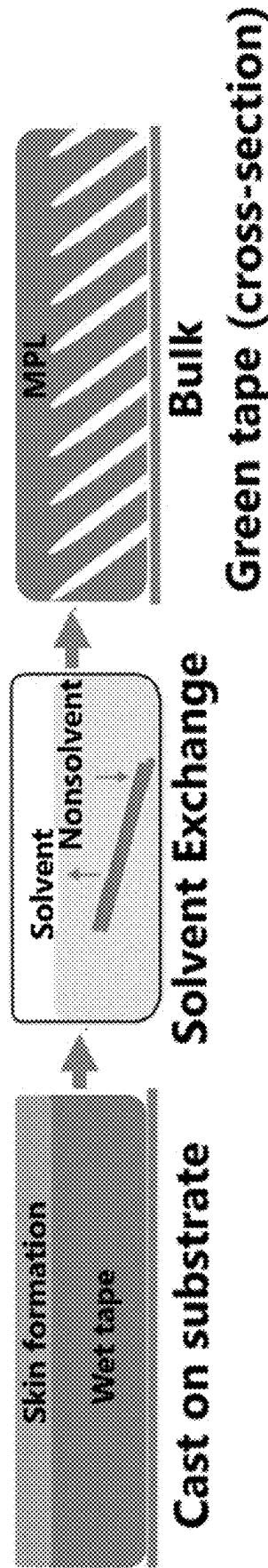


FIGURE 14

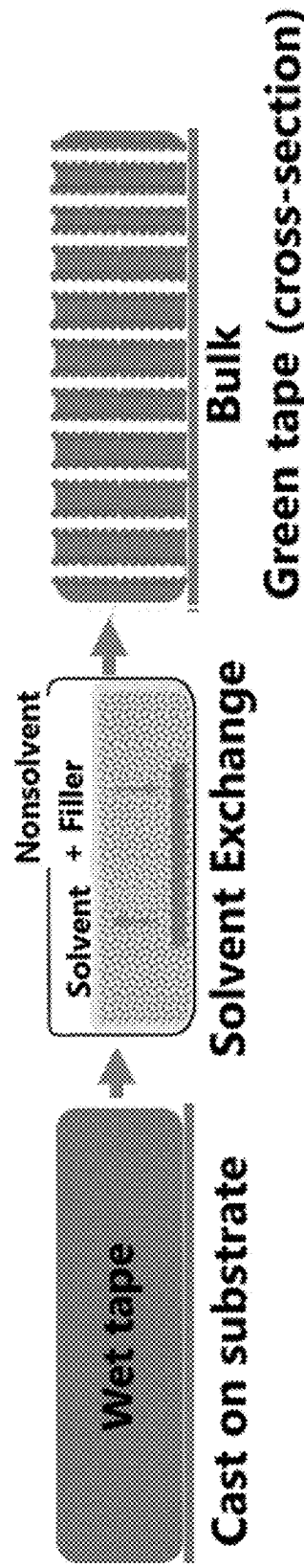


FIGURE 15

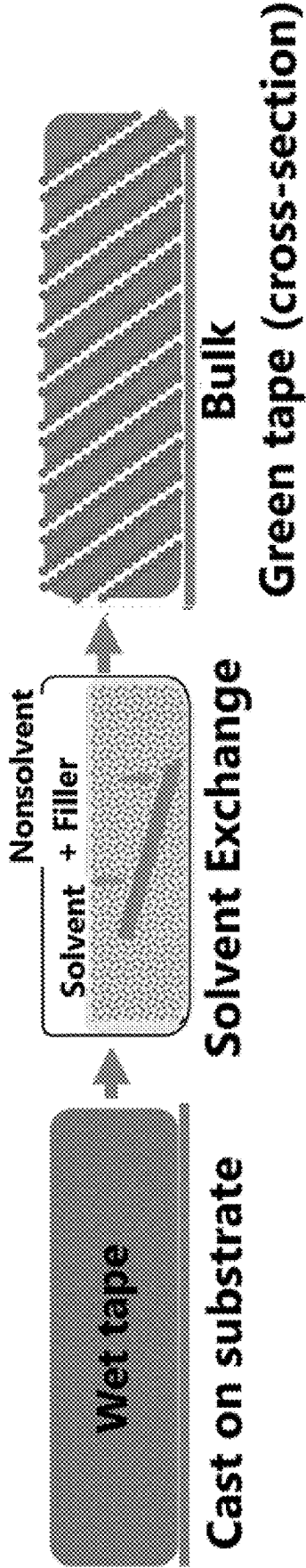


FIGURE 16

**POROUS LAYERS WITHIN
ELECTROCHEMICAL CELLS HAVING
DIRECTIONALLY ORIENTED CHANNELS**

[0001] The present patent document claims the benefit of U.S. Provisional Patent Application No. 63/556,058, filed Feb. 21, 2024, which is hereby incorporated by reference in its entirety.

FIELD

[0002] The following disclosure relates to electrochemical or electrolysis cells and components thereof. More specifically, the following disclosure relates to porous transport layers (PTLs) and gas diffusion layers (GDLs) having directionally oriented channels.

BACKGROUND

[0003] Hydrogen has been considered as an ideal energy carrier to store renewable energy. Proton exchange membrane water electrolysis (PEMWE) as a means for hydrogen production offers high product purity, fast load response times, small footprints, high efficiencies, and low maintenance efforts. It is regarded as a promising technology, especially when coupled with renewable energy sources.

[0004] An electrolysis cell or system uses electrical energy to drive a chemical reaction. For example, water is split to form hydrogen and oxygen. The products may be used as energy sources for later use. In recent years, improvements in operational efficiency have made electrolyzer systems competitive market solutions for energy storage, generation, and/or transport. For example, the cost of generation may be below \$10 per kilogram of hydrogen in certain cases. Increases in efficiency and/or improvements in operation will continue to drive the installation of electrolyzer systems.

[0005] Porous transport layers (PTLs) play important roles in electrochemical cell performance. A PTL, positioned between an anode catalyst layer and an anode flow field of the electrochemical cell, may assist in transporting water and oxygen on the anode side and in transporting electrons away from the anode catalyst layer. A GDL, positioned between a cathode catalyst layer and a cathode flow field of the electrochemical cell, may assist in transporting hydrogen on the cathode side of the cell and in transporting electrons towards the cathode catalyst layer.

[0006] There remains a desire for improved performance properties within electrochemical cells, including improved fluid transport within the cell.

SUMMARY

[0007] In one embodiment, a porous layer includes a porous composition having a plurality of micropores and a plurality of channels having opening diameters that are larger than an average pore diameter of the plurality of micropores. The plurality of channels extends through at least 50% of a depth of the porous layer as measured in a direction perpendicular to a plane in which the porous layer is oriented. The porous layer is configured to convey a two-phase mixture of liquid and gas within the electrochemical cell. Further, each channel of the plurality of channels is configured to facilitate a transfer of gas from the porous layer into an adjacent flow field of the electrochemical cell.

[0008] In another embodiment, an electrochemical cell includes a flow field, a membrane, and a porous layer positioned between the flow field and the membrane. The porous layer includes a porous composition having a plurality of micropores and a plurality of channels having opening diameters that are larger than an average pore diameter of the plurality of micropores, wherein the plurality of channels extends through at least 50% of a depth of the porous layer as measured in a direction perpendicular to a plane in which the porous layer is oriented, wherein the porous layer is configured to convey a two-phase mixture of liquid and gas within the electrochemical cell, and wherein each channel of the plurality of channels is configured to facilitate a transfer of gas from the porous layer into the flow field of the electrochemical cell.

[0009] In another embodiment, a method of manufacturing a porous layer includes: casting a slurry composition having a solvent composition onto a substrate to provide a wet tape on the substrate; submerging the wet tape on the substrate into a bath solution having a non-solvent composition, wherein a directional exchange takes place in which a portion of the solvent composition within the wet tape is removed from the wet tape via interaction with the non-solvent composition within the bath to form a wet tape having a plurality of parallel channels; removing the wet tape having the plurality of parallel channels from the bath solution; and sintering the wet tape having the plurality of parallel channels to form the porous layer.

[0010] In another embodiment, a method of manufacturing a porous layer includes: providing a fibrous mat having microfibers and/or nanofibers that are patterned to have one or more channel orientations; providing a slurry composition; applying the slurry composition into pores of the fibrous mat to form a green tape having a plurality of channels within the green tape; and sintering the green tape to form the porous layer.

[0011] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Exemplary embodiments are described herein with reference to the following drawings.

[0013] FIG. 1 depicts an example of an electrochemical system including an electrochemical stack having a plurality of electrochemical cells.

[0014] FIG. 2 depicts an example of an electrolytic cell.

[0015] FIG. 3 depicts an additional example of an electrolytic cell.

[0016] FIGS. 4A, 4B, and 4C depict cross-sectional views of an example of an electrochemical cell with a limited number of flow channels of flow fields depicted for clarity.

[0017] FIG. 5 illustrates a bubble distribution in an electrochemical cell.

[0018] FIGS. 6A and 6B illustrate bubble distributions in two identical electrochemical cells operating at different power levels.

[0019] FIGS. 7A-10B depict examples of various porous layer having a plurality of open channels or cavities within the layer.

[0020] FIGS. 11-16 depict examples of various methods of forming porous layers having a plurality of open channels.

DETAILED DESCRIPTION

[0021] The following disclosure provides improved porous layers (e.g., porous transport layers (PTLs) and gas diffusion layers (GDLs)) in an electrochemical or electrolytic cell for hydrogen gas and oxygen gas production through the splitting of water. Further, the following disclosure provides various processes for making the improved porous layers, e.g., including directionally oriented channels within the PTL or GDL.

[0022] A plurality of channels or cavities within the porous layer (e.g., the PTL or GDL) as disclosed herein may allow for one or more advantages including, but not limited to: improved mechanical strength within the porous layer and electrochemical cell; improved/reduced resistivity within the cell; increased pore volume within the porous layer; smaller pore sizes within the microporous layer adjacent to the flow field and/or the membrane resulting in improved membrane longevity; improved/increased potential wettability; improved/increased corrosion resistance; and/or improved/larger water processing volume or throughput through the cell.

[0023] For instance, the plurality of channels or cavities may advantageously provide improved transportation of liquid water from the flow field toward the membrane and an improved transportation of gas (e.g., oxygen or hydrogen) from the membrane toward the flow field (i.e., for gas bubbles to flow through the layer without being trapped). Accordingly, the gaseous product or gas bubbles formed in the water splitting reaction in the electrochemical cell may flow from nucleation sites or high gas saturation regions through the channels and to a surface of the porous layer adjacent to a flow field of the electrochemical cell. The gaseous product may then flow through the channels of the flow field, exiting the cell. Thus, the channels may advantageously facilitate an improved fluid transfer or removal of gas (e.g., gaseous product) from the porous layer in comparison with a similar electrochemical cell not including such cavities in the porous layer (e.g., PTL or GDL) of the cell. The channels may advantageously reduce an average duration of time required for gas bubbles to exit the porous layer of the electrochemical cell and thus the cell in its entirety, therein improving the efficiency of the electrochemical cell.

[0024] Channels within the surface of the porous layer may advantageously allow for an increase in an amount of reactant water supplied to the membrane/catalyst layer of the cell, therein allowing the cell to operate at higher power levels without a mass transfer limitation occurring, improving efficiency of the electrochemical cell. Additionally, improving efficiency of the removal of gaseous products from the cell may advantageously create a more uniform gas-liquid distribution in the porous layers of the cell. Engineered cavities or channels may provide pathways for gas to be released preventing large regions to be occupied by gas. This may avoid generation of hot spots and may advantageously provide a more uniform temperature distribution across the cell.

[0025] Improved porous layers with such channels, electrochemical cells and stacks including such improved porous layers, and methods of making the improved porous layers are disclosed in greater detail below.

Definitions

[0026] As used herein, “providing” may refer to the provision of, generation or, presentation of, or delivery of that which is provided. Providing may include making something available. For example, providing a powder may refer to a process of making the powder available, or delivering the powder, such that the powder can be used as set forth in a method described herein. As used herein, providing also may refer to measuring, weighing, transferring, combining, or formulating.

[0027] As used herein, “casting” may refer to depositing or delivering a cast solution or slurry onto a substrate. Casting may include, but is not limited to, slot die coating, gravure coating, tape casting, dip coating, and slip casting (e.g., pressurized slip casting).

[0028] As described herein, the term “channel” or “channels” may refer to cavities, macro-voids, or macro-pores within the porous layer (e.g., porous transport layer, gas diffusion layer) that are configured to promote facile release of gas products from the porous layer into the adjacent flow field. In certain examples, the average width or diameter of the channel (e.g., at the surface) of the porous layer is greater than the width or diameter of an opening or pore between two adjacent particles or fibers within the porous layer. In certain examples, the average width or diameter of the opening of the channel is at least two times, at least five times, at least 10 times, at least 20 times, at least 50 times, or at least 100 times greater than the average pore size or opening between adjacent particles or fibers within the porous layer. In certain examples, the average width or diameter of the opening of the channel may be at least 0.1 micron, at least 1 micron, at least 5 microns, at least 10 microns, in a range of 0.1-10 microns, or in a range of 0.1-5 microns. Additionally, in certain examples, the channel may extend through the entire depth of the porous layer. Alternatively, the channel may extend a certain distance less than the entire depth of the porous layer, wherein the distance is at least 50%, at least 60%, at least 70%, at least 80%, at least 90% of the depth of the porous layer, in a range of 50-99%, in a range of 60-99%, in a range of 70-99%, or in a range of 80-99% of the depth of the porous layer. In alternative examples, the channel may extend a certain distance less than the entire depth of the porous layer, wherein the distance is at least 500 microns, at least 300 microns, at least 150 microns, at least 50 microns, at least 10 microns, in a range of 10-500 microns, in a range of 10-300 microns, in a range of 10-150 microns, or in a range of 10-50 microns.

[0029] As used herein, “solvent” may refer to a liquid that is suitable for dissolving or solvating a component or material described herein. For example, a solvent may include a liquid, (e.g., toluene), which is suitable for dissolving a component, (e.g., the binder).

[0030] As used herein, a “binder” may refer to a material that assists in the adhesion of another material. For example, as used herein, one non-limiting binder may be polyvinyl butyral. Other binders may include polycarbonates and/or polymethylmethacrylates. These examples of binders are not limiting as to the entire scope of binders contemplated here but merely serve as examples. Binders useful in the present disclosure may include, but are not limited to, polypropylene (PP), atactic polypropylene (aPP), isotactic polypropylene (iPP), ethylene propylene rubber (EPR), ethylene pentene copolymer (EPC), polyisobutylene (PIB), styrene butadiene rubber (SBR), polyolefins, polyethylene-co-poly-1-octene

(PE-co-PO), PE-co-poly(methylene cyclopentane) (PE-co-PMCP), poly methyl-methacrylate (and other acrylics), acrylic, polyvinyl acetal resin, polyvinyl butyral resin (PVB), polyvinyl acetate resin, stereoblock polypropylenes, polypropylene polymethyl pentene copolymer, polyethylene oxide (PEO), PEO block copolymers, silicone, and the like.

[0031] As used herein, “green state” may refer to a composition or structure that has not undergone any subsequent heat treatment to harden or form the composition into a solid or porous mass. Specifically, “green state” may refer to a composition or structure that has not been sintered. Non-limiting examples disclosed herein may refer to an unsintered fiber felt composition (e.g., unsintered titanium fiber felt), an unsintered particle composition or structure (e.g., unsintered titanium powder), or combinations thereof.

[0032] As used herein, “sintered state” may refer to a sintered composition or structure, such as a sintered fiber felt (e.g., sintered titanium felt), sintered structure (e.g., titanium powder that has been sintered into a solid or porous mass), or combinations thereof.

[0033] As used herein, “sintering” may refer to heating a starting composition (e.g., a powdered material or fiber felt) to coalesce the starting composition into a solid or porous mass without liquefaction, (e.g., heating the starting composition to a temperature below the melting point of a compound within the starting composition—such as a temperature below the melting point of titanium).

[0034] As used herein, a “thickness” by which is film is characterized refers to the distance, or median measured distance, between the top and bottom faces of a film in a direction perpendicular to the plane of the film layer. As used herein, the top and bottom faces of a film refer to the sides of the film extending in a parallel direction of the plane of the film having the largest surface area.

Electrochemical Cells

[0035] FIG. 1 depicts an example of an electrochemical system including an electrochemical stack having a plurality of electrochemical cells. In certain examples, the electrochemical stack may contain 50-1000 cells, 50-100 cells, 500-700 cells, or more than 1000 cells. Any number of cells may make up a stack. The electrochemical cells within the electrochemical stack may be configured to operate with 200 mV or less of pure resistive loss when operating at a high current density (e.g., at least 3 Amps/cm², at least 4 Amps/cm², at least 5 Amps/cm², at least 6 Amps/cm², at least 7 Amps/cm², at least 8 Amps/cm², at least 9 Amps/cm², at least 10 Amps/cm², at least 11 Amps/cm², at least 12 Amps/cm², at least 13 Amps/cm², at least 14 Amps/cm², at least 15 Amps/cm², at least 16 Amps/cm², at least 17 Amps/cm², at least 18 Amps/cm², at least 19 Amps/cm², at least 20 Amps/cm², at least 25 Amps/cm², at least 30 Amps/cm², in a range of 1-30 Amps/cm², in a range of 3-20 Amps/cm², in a range of 3-15 Amps/cm², in a range of 3-10 Amps/cm², or in a range of 10-20 Amps/cm²). In additional examples, the amount of water (e.g., deionized (DI) water) transferred to or circulated through each cell of the stack may be in a range of 0.25-5 mL/Amp/cell/min.

[0036] As illustrated in the system of FIG. 1, water (H₂O) may be supplied to the anodic inlet of an electrolytic cell stack 12. In certain embodiments, only the anodic inlet of the cell stack 12 may receive water. In these embodiments, the cathode side of the cell stack 12 may not receive water (e.g., a dry cathode side may be used). In another embodiment, a

cathode inlet may also receive water, wherein the water may be supplied to the cathode inlet to cool the cell stack 12 during electrolysis.

[0037] The water supplied to the anodic inlet flows to an anodic inlet manifold that distributes the water to the anode side of the plurality of cells contained within the cell stack 12. In embodiments where water is supplied to the cathode inlet, water supplied to the cathode inlet flows to a cathodic inlet manifold that distributes the water to the cathode side of the plurality of cells in the cell stack 12. In certain examples, the amount of water (e.g., deionized (DI) water) transferred to or circulated through each cell of the stack may be in a range of 0.25-5 mL/Amp/cell/min.

[0038] During electrolysis, oxygen (O₂) is produced at the anode side of the electrolytic cells and hydrogen (H₂) is produced at the cathode side of the electrolytic cells. Specifically, a water splitting electrolysis reaction is configured to take place within each individual cell in the cell stack 12. Each cell includes one interface (the anode side of the cell) configured to run an oxygen evolution reaction (OER) and another interface (the cathode side of the cell) configured to run a hydrogen evolution reaction (HER) (such as depicted in FIG. 2).

[0039] During electrolysis, a portion of the water supplied to the anode side of an electrolytic cell may not be converted into oxygen. Accordingly, a two-phase flow of oxygen and unreacted water is outlet from each of the anode sides of the cells into an anodic outlet manifold 13. The two-phase flow of oxygen and unreacted water flows from out of the cell stack 12 through the anodic outlet manifold 13. This stream within the anodic outlet manifold 13 may be configured to be transferred to a gas detection and conditioning system, such as described in greater detail below, for analysis of the composition within the stream. Specifically, this anodic stream may be analyzed to identify if any undesirable hydrogen gas has leaked (i.e., cross-leaked) across the membranes from the cathode sides of the cells to the anode sides of the cells within the cell stack.

[0040] Additionally, in certain embodiments, water may be supplied to the cathode side of the cell stack as a coolant. Accordingly, a two-phase flow of hydrogen and water is outlet from each of the cathode sides of the cells to a cathodic outlet manifold 14. The two-phase flow of hydrogen and water flows out of the cell stack 12 through the cathodic outlet manifold 14. Similarly, this particular stream within the cathodic outlet manifold 14 may be configured to be transferred to a gas detection and conditioning system (separate from the anodic gas detection and conditioning system) for analysis of the composition within the stream. Specifically, this cathodic stream may be analyzed to identify if any undesirable oxygen gas has leaked (i.e., cross-leaked) across the membranes from the anode sides of the cells to the cathode sides of the cells within the cell stack.

[0041] FIG. 2 depicts an example of an electrochemical or electrolytic cell for hydrogen gas and oxygen gas production through the splitting of water. The electrochemical cell within FIG. 2 may be one of the plurality of cells within the electrochemical stack in FIG. 1. The electrochemical cell includes a cathode, an anode, and a membrane positioned between the cathode and anode. The membrane may be a proton exchange membrane (PEM) that may have a catalyst coating on one or both surfaces of the PEM. In other examples, the membrane may be positioned within an electrochemical cell having a catalyst coating on an adjacent

supporting layer within the cell (e.g., a gas diffusion layer or porous transport layer near or abutting the membrane).

[0042] Proton Exchange Membrane (PEM) electrolysis involves the use of a solid electrolyte or ion exchange membrane. Within the water splitting electrolysis reaction, one interface runs an oxygen evolution reaction (OER) while the other interface runs a hydrogen evolution reaction (HER). For example, the anode reaction is $\text{H}_2\text{O} \rightarrow 2\text{H}^+ + \frac{1}{2}\text{O}_2 + 2\text{e}^-$ and the cathode reaction is $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$.

[0043] FIG. 3 depicts an additional example of an electrochemical or electrolytic cell. Specifically, FIG. 3 depicts a portion of an electrochemical cell 300 having a cathode flow field 302 and an anode flow field 304, and a membrane 306 positioned between the cathode flow field 302 and the anode field 304.

[0044] In certain examples, the membrane 306 may be a catalyst coated membrane (CCM) having a cathode catalyst layer 305 and/or an anode catalyst layer 307 positioned on respective surfaces of the membrane 306. Alternatively, the membrane may not include a catalyst coating layer on one or both sides of the membrane. In certain examples, the cell may still include a cathode catalyst layer and/or anode catalyst layer, but one or both of these layers may be coated or positioned on an adjacent supporting layer within the cell (e.g., the gas diffusion layer or the porous transport layer).

[0045] In certain examples, additional layers may be present within the electrochemical cell 300. For example, one or more additional layers 308 may be positioned between the cathode flow field 302 and membrane 306. In certain examples, this may include a gas diffusion layer (GDL) 308 positioned between the cathode flow field 302 and membrane 306. This may be advantageous in providing a hydrogen diffusion barrier adjacent to the cathode on one side of the multi-layered membrane to assist in transferring or releasing the generated hydrogen gas toward the cathode flow field and out of the cell.

[0046] In certain examples, the PTL 310 may include a porous titanium fiber felt, a porous sintered titanium particle sheet, or a combination thereof. The PTL 310 is configured to allow the transportation of reactant water to the anode catalyst layers, remove produced oxygen gas, and provide good electrical conductivity for effective electron conduction. The thickness of the PTL 310 may be in the range of 1-1000 microns, 1-100 microns, 10-100 microns, 10-1000 microns, or 100-1000 microns, for example. The thickness may affect the mass transport within the cell as well as the durability/deformability and electrical/thermal conductivity of the PTL 310. In other words, a thinner PTL 310 may provide better mass transport and a reduction in durability (e.g., greater chance for localized deformation).

[0047] In certain examples, an anode catalyst coating layer may be positioned between the anode flow field 304 and the PTL 310.

[0048] Similarly, one or more additional layers may be present in the electrochemical cell between the membrane 306 and the cathode flow field 302. In certain examples, this may include a gas diffusion layer (GDL) 308 positioned between the cathode flow field 302 and membrane 306. This may be advantageous in providing diffusion pathways for hydrogen to move away from a cathode catalyst layer, into the cathode flow field.

[0049] In certain examples, the GDL 30 is made from a carbon paper or woven carbon fabrics. The GDL 308 is configured to allow the flow of hydrogen gas to pass through

it. The thickness of the GDL 308 may be within a range of 100-1000 microns, for example. The thickness may affect the mass transport within the cell as well as the durability/deformability and electrical/thermal conductivity of the GDL 308. In other words, a thinner GDL 308 may provide better mass transport, lower resistance, and a reduction in durability (e.g., greater chance for localized deformation).

[0050] The cathode flow field 302 and anode flow field 304 of the cell may individually include a flow field plate composed of metal, carbon, or a composite material having a set of channels machined, stamped, or etched into the plate to allow fluids to flow inward toward the membrane or out of the cell.

[0051] FIGS. 4A, 4B, and 4C depict such an example of an electrochemical or electrolytic cell, wherein examples of flow fields are depicted. In this particular example, the electrochemical cell includes a cathode flow field 302, cathode flow channels 303, an anode flow field 304, anode flow channels 305, and a membrane 306 positioned between the cathode and the anode. Additionally, the electrochemical cell 300 includes a gas diffusion layer 308 positioned between the catalyst coated membrane 306 and the cathode flow channels 303. Further, a porous transport layer 310 is positioned between the catalyst coated membrane 306 and the anode flow channels 305. The porous transport layer 310 may be the same as the porous transport layer 210 and the gas diffusion layer 308 may be the same as the gas diffusion layer 208.

[0052] In the particular example depicted in FIGS. 4A and 4B, the cathode and anode flow fields are arranged to provide a cross-fluid flow. In such a cross-fluid arrangement, the fluid flow through the cathode flow channels is arranged perpendicular to the fluid flow through the anode flow channels. Specifically, FIG. 4A depicts the cross-sectional view of the electrochemical cell with the cathode flow channels displayed, while FIG. 4B depicts the cross-sectional view of the electrochemical cell rotated 90 degrees to display the anode flow channels.

[0053] In alternative examples, the flow fields may have a co-flow configuration or a counter-flow configuration. FIG. 4C depicts an alternative example, wherein the channels and lands of the anode flow field are parallel with the channels and lands of the cathode flow field, therein allowing for a co-flow or a counter-flow configuration. In a co-flow configuration, the flow of fluid through the anode flow field channels is in the same direction as the flow of fluid through the cathode flow field channels. Alternatively, a counter-flow configuration may be present with the parallel arrangement of the anode and cathode flow fields, wherein the flow of fluid through the anode flow field channels is in an opposite direction as the flow of fluid through the cathode flow field channels.

[0054] The orientation or configuration of the fluid flow between the anode flow field and cathode flow field may be advantageous in adjusting or controlling the pressure distribution or temperature distribution within the electrochemical cell.

[0055] Regarding these anode and cathode flow fields depicted on FIGS. 4A and 4B, such flow fields may be configured to have the paths of channels and lands. The channels are configured for directing the flow of fluid (e.g., water and gas), while the lands are configured to contact an adjacent layer of the electrochemical cell (e.g., a porous layer, PTL 310, GDL 308). FIGS. 4A and 4B depict

examples of cells having three cathode flow channels and three anode flow channels, respectively. The number of flow channels are depicted for simplicity of design, and in potential commercial use, may include many more flow channels. As such, the disclosure is not limited to such configurations as depicted in FIGS. 4A and 4B.

[0056] During proton exchange membrane water electrolysis (PEMWE) an oxygen evolution reaction (OER) may occur on an anode interface or side of an electrochemical or electrolytic cell and a hydrogen evolution reaction (HER) may occur on a cathode interface or side of the cell. For an oxygen evolution reaction (OER) occurring at an anode interface (e.g., at an anode catalyst layer) water is a reactant and is often in liquid phase. In certain examples, water may be provided to a cathode interface of the cell, e.g., as a cooling source for the cathode side of the cell.

[0057] FIG. 5 illustrates a section of one interface (e.g., anode interface, cathode interface) of an electrochemical or electrolytic cell 400. The cell 400 may include a flow field 410, a porous layer 420 (e.g., a porous transport layer or gas diffusion layer), a catalyst layer 430, and a proton exchange membrane 440.

[0058] The flow field 410 may be an anode flow field (e.g., anode flow field 204, 304) or a cathode flow field (e.g., cathode flow field 202, 302). As disclosed herein, the flow field 410 may be any type of flow field known in the art for use in an electrochemical cell.

[0059] In certain examples, the flow field 410 may include a plurality of lands 411 and a plurality of flow field channels 412. As illustrated in FIG. 5, the flow field 410 include two lands 411 and a single flow field channel 412; however, the present disclosure is not limited thereto. Additional lands 411 and flow field channels 412 may be included. The lands 411 define or separate flow field channels 412 of flow field 410. The lands 411 may be adjacent to and in contact with the porous layer 420 of the cell 400. The flow field channels 412 of the cell may be connected to an inlet and/or outlet of the flow field 410. The flow field channels 412 are configured to convey a flow of fluid. The flow field channels 412 may be configured to both convey a flow of fluid into the porous layer 420 and receive a flow of fluid from the porous layer 420. For example, when the flow field 410 is an anode flow field, the flow field channels 412 may be configured to both convey a flow of water from an inlet of the flow field 410 into the porous transport layer 420 and receive a flow of oxygen and water from the porous transport layer 420 from the water splitting reaction at the membrane and convey the oxygen and water to an outlet of the anode flow field 410.

[0060] In another example, when the flow field 410 is a cathode flow field, the flow field channels 412 may be configured to receive a flow of hydrogen (and, in some cases, water) from the porous transport layer 420 from the water splitting reaction at the membrane and convey the hydrogen (and potentially water) to an outlet of the flow field 410. In other examples, when the flow field 410 is a cathode flow field, the flow field channels 412 may be configured to both convey a flow of water from an inlet of the flow field 410 into the porous transport layer 420 and receive a flow of hydrogen (and, e.g., water) from the porous transport layer 420 and convey the hydrogen (and, e.g., water) to an outlet of the cathode flow field.

[0061] The porous layer 420 may be a porous transport layer (PTL) (e.g., PTL 210, 310) or a gas diffusion layer (GDL) (e.g., GDL 208, 308). The porous layer 420 may be

disposed between the flow field 410 and the catalyst layer 430. The porous layer 420 may be configured to convey fluid. For example, the porous layer 420 may be configured to convey a flow of fluid from the flow field channels 412 of the flow field 410 to the catalyst layer 430 and/or convey a flow of fluid from the catalyst layer 430 to the flow field channels 412 of the flow field 410. For example, when the porous layer 420 is a PTL, the porous layer may be configured to convey a flow of liquid water from the flow field channels 412 of the flow field 410 to the catalyst layer 430 and convey a flow of gaseous oxygen from the catalyst layer 430 to the flow field channels 412 of the flow field 410. In another example, when the porous layer 420 is a gas diffusion layer, the porous layer may be configured to convey a flow of gaseous hydrogen from the catalyst layer 430 to the flow field channels 412 of the flow field 410.

[0062] The catalyst layer 430 may refer to an anode catalyst layer (e.g., anode catalyst layer 207) or a cathode catalyst layer (e.g., cathode catalyst layer 205). The catalyst layer 430 may be a catalyst for facilitating the water splitting reaction occurring on a given interface of the cell 400. For example, when the catalyst layer is an anode catalyst layer, the catalyst layer 430 may be a catalyst for the oxygen evolution reaction (OER) occurring at the anode interface of the cell. In another example, when the catalyst layer 430 is a cathode catalyst layer, the catalyst layer 430 may be a catalyst for the hydrogen evolution reaction (HER) occurring at the cathode interface of the cell 400. Gaseous products (e.g., hydrogen, oxygen) may be produced at or near the catalyst layer 430.

[0063] The proton exchange membrane 440 may be disposed between an anode catalyst layer and a cathode catalyst layer of the cell 400. The proton exchange membrane 440 may be configured to convey or transport protons from the anode interface of the cell 400 to the cathode interface of the cell 400. In certain examples, the proton exchange membrane 440 may be a catalyst coated membrane and include the anode catalyst layer and/or the cathode catalyst layer.

[0064] FIG. 5 illustrates operation of one interface of the cell 400 during water electrolysis. During operation of the cell 400, water may flow through the flow field channels 412 of the flow field 410 into the porous layer 420 of the cell 400. The porous transport layer 420 may convey the flow of water toward the catalyst layer 430. When the water reaches the catalyst layer 430, a gas generating reaction (e.g., the water splitting reaction) may occur. For example, at an anode interface, an oxygen evolution reaction (OER) may occur. For example, two moles of water may be split into four moles of protons, four moles of electrons, and one mole of oxygen. Similarly, for the water splitting reaction, a hydrogen evolution reaction (HER) may occur at a cathode interface of the cell.

[0065] Products of the cell 400, (e.g., oxygen generated by an OER reaction at the anode interface of the cell 400 or hydrogen generated by a HER at the cathode interface of the cell 400), may be generated in a generation region at or near the catalyst layer 430. Thus, as the gas generating reactions (e.g., OER, HER), a two-phase mixture of liquid and gas may be created in the porous transport layer 420. Gas generated by the cell 400 may flow through the porous transport layer 420 to the flow field channels 412 of the flow field 410 and through the flow field channels 412 to exit an outlet of the flow field 410.

[0066] The physical morphology (e.g., cavity size and cavity distribution) of the porous layer 420 may dictate preferential pathways of gaseous product transport through the porous layer 420 to the flow field channels 412 of the flow field 410. Accordingly, morphology of the porous layer may be tailored or adjusted to better remove gaseous product away from generation regions or reaction sites (e.g., the catalyst layer 430). As gas bubbles move or travel through the porous layer, when the radius of a gas bubble in a cavity of the porous layer is larger than the radius of a capillary tube connected to the cavity, the bubble may be trapped in the cavity. Further, if another gas bubble moves into the cavity including the trapped bubble, the two bubbles may merge together and may form a bigger trapped bubble if the volume of the merged gas bubble is smaller than the volume of the cavity. Gas bubbles may also become trapped under the land areas for a channel flow field, where convective flow is less compared to areas under the channel areas. Consequently, the morphology of the porous layer may be tailored to better provide liquid water to reaction sites. For example, porous layer morphology may be designed to provide smaller cavity sizes/low porosity to facilitate liquid water transport and high porosity to facilitate gas transport by enabling merging of gaseous bubbles. Additionally, the porous layer channels may be oriented in such a way as to prevent the trapping of gas bubbles under the flow field lands.

[0067] Supply of liquid reactant water and removal of gaseous products are crucial for durable and high current density operation of the electrochemical or electrolytic cell. For example, residual oxygen bubbles near a catalyst layer can block water from reacting with the electrocatalyst (e.g., catalyst layer 430) decreasing the efficiency of the cell. Additionally, reactant water may be used to cool the cell. Accordingly, residual bubbles of gaseous products may prevent the flow of water through portions of the porous layer, impacting the thermal performance of the cell.

[0068] As illustrated in FIG. 5, the gas bubbles 450 are formed at or near the catalyst layer 430. The gas bubbles 450 may then travel through the porous layer 420 to the flow field channels 412 of the flow field 410. As the gas bubbles 450 travel through the porous layer 420 toward the flow field 410, they may merge forming larger gas bubbles 450. Accordingly, as illustrated in FIG. 5, a larger number of small gas bubbles 450 may be present near the catalyst layer 430 and a smaller number of larger gas bubbles 450 may be present further away from the catalyst layer (e.g., toward the flow field 410). In other words, gas bubbles nucleating from a generation region) at or near the catalyst layer 430 may coalesce and increase in size as they travel through the porous transport layer 420 toward the flow field 410.

[0069] FIGS. 6A and 6B illustrate bubble distributions in two identical electrochemical or electrolytic cells (e.g., cell 400) operating at two different power levels. The power levels at which the cells operate may be a function of the current flowing through the cell. FIG. 6A illustrates a cell 400 operating at a relatively low power and FIG. 6B illustrates a cell 400 operating at a relatively high power. As illustrated in FIGS. 6A and 6B, when the cell 400 is operating at a higher power with identical cell components, more product gas (e.g., oxygen, hydrogen) will be generated. Further, as illustrated in FIGS. 6A and 6B, if the water flow rate through the cell 400 is assumed to be the same, at higher operating power, more porous volume inside the

porous layer and more space in the flow field channels will be occupied by gas bubbles 450. The gas bubbles 450 in the porous layer 420 may prevent reactant water from flowing to the catalyst layer 430, causing a mass transfer limitation of the reaction (e.g., oxygen evolution reaction) occurring at or near the catalyst layer 430, limiting the amount of product gas (e.g., oxygen, hydrogen) that may be produced.

Porous Layers with Directionally Oriented Channels

[0070] To accommodate an improved transportation of liquid water from the flow field toward the membrane and an improved transportation of gas (e.g., oxygen or hydrogen) from the membrane toward the flow field, the porous transport layer or the gas diffusion layer may be configured to have open channels or cavities extending through at least a portion of the layer.

[0071] FIG. 7A depicts an example of such a porous layer having a plurality of open channels or cavities within the layer. In certain examples, the porous layer refers to a porous transport layer within the electrochemical cell, positioned between the membrane and an anode flow field. In other examples, the porous layer refers to a gas diffusion layer positioned between the membrane and a cathode flow field of the electrochemical cell.

[0072] In this particular example, the plurality of channels extends through the entire depth of the porous layer. The channels may be configured to be parallel to each other. Further, as depicted in FIG. 7A, the parallel channels may be oriented perpendicular to the plane in which the porous layer is positioned. That is, each channel advantageously may provide the shortest travel path for fluid between the adjacent layers within the electrochemical cell (e.g., the flow field and membrane layers).

[0073] As described above, each channel may have an average width or diameter that is greater than the width or diameter of an opening or pore between two adjacent particles or fibers within the porous layer. For example, the average width or diameter of the opening of the channel (e.g., as measured at a surface of the porous layer) may be at least two times, at least five times, at least 10 times, at least 20 times, at least 50 times, or at least 100 times greater than the average pore size or opening between adjacent particles or fibers within the porous layer (i.e., micropores). This may equate to an average width or diameter of the channel being at least 0.1 micron, at least 1 micron, at least 5 microns, at least 10 microns, in a range of 0.1-50 microns, in a range of 0.1-10 microns, or in a range of 0.1-5 microns.

[0074] The number of channels and positioning of the channels within the porous layer may be configurable. Additionally, the shape and/or size of channels within the porous layer may also be configurable. The location distribution, number of channels, the shape of the channels, and the size (e.g., width/diameter and/or depth) of channels may be selected or configured based on the electrochemical cell in which they are used. For example, the location distribution, number of channels, shape of channels, and size of channels used may be a selected based on the type of electrochemical cell, flow field of the electrochemical cell, flow rate of reactant supplied to the electrochemical cell, power of the electrochemical cell, number of cells in an electrochemical cell stack, and the like, (e.g., based on a desired or required bubble release speed and/or water flow rate).

[0075] The distance between adjacent channels may also be configurable. In certain examples, the distances between

adjacent channels may be equidistant (or approximately equidistant, e.g., within upwards of a 10% variation in distances). In alternative examples, the distances between adjacent channels may be variable or random. The average distance between adjacent channels (as measured from the adjacent edges of adjacent channels) may be the same as the average width/diameter of the channel or may be at least two times, at least five times, or at least 10 times the average width/diameter of the channel within the porous layer. This may equate to an average distance between adjacent channels being at least 1 micron, at least 5 microns, at least 10 microns, at least 20 microns, at least 50 microns, at least 100 microns, in a range of 1-100 microns, in a range of 10-100 microns, or in a range of 50-100 microns.

[0076] As noted above, this particular arrangement of channels or cavities within the porous layer may advantageously allow for an improved mechanical strength within the porous layer (as well as the overall electrochemical cell). Specifically, through the use of larger channels or openings for fluid flow, the remainder of the porous structure may be more densely configured. That is, smaller fibers, particles, or powders may be used in the formation of the porous layer, leading to smaller pore sizes within the porous layer, and advantageously adding to an overall stronger structure. Additionally, this may provide for additional advantages such as reduced resistivity within the cell, improved membrane protection, improved/increased potential wettability, and/or improved/increased corrosion resistance.

[0077] Also, the addition of a plurality of channels within the porous layer may advantageously allow for an increased overall pore volume within the porous layer. That is, while the pore density or volume may be smaller within the remaining area of the porous layer, the addition of open channels through the porous layer may allow for an overall increase in open space/pore volume within the layer.

[0078] Additionally, or alternatively, the implementation or addition of the plurality of channels within the porous layer may advantageously allow for a higher operational throughput of water through the electrochemical cell. That is, a larger volume of water per period of time may be processed and reacted within the cell due to an improved ability to transfer water and gas products within the cell through the porous layer (i.e., due to the channels themselves or the combination of the channels and overall increased pore volume within the layer). Specifically, the plurality of channels may advantageously provide improved transportation of liquid water from the flow field toward the membrane and an improved transportation of gas (e.g., oxygen or hydrogen) from the membrane toward the flow field (i.e., for gas bubbles to flow through the layer without being trapped). Accordingly, the gaseous product or gas bubbles formed in the water splitting reaction in the electrochemical cell may flow from nucleation sites or high gas saturation regions through the channels and to a surface of the porous layer adjacent to a flow field of the electrochemical cell. The gaseous product may then flow through the channels of the flow field, exiting the cell.

[0079] Thus, the channels may advantageously facilitate an improved fluid transfer or removal of gas (e.g., gaseous product) from the porous layer in comparison with a similar electrochemical cell not including such cavities in the porous layer (e.g., PTL or GDL) of the cell. The channels may advantageously reduce an average duration of time required for gas bubbles to exit the porous layer of the

electrochemical cell and thus the cell in its entirety, therein improving the efficiency of the electrochemical cell. This may advantageously allow for an increase in an amount of reactant water supplied to the membrane/catalyst layer of the cell, therein allowing the cell to operate at higher power levels without a mass transfer limitation occurring, improving efficiency of the electrochemical cell. Additionally, improving efficiency of the removal of gaseous products from the cell may advantageously create a more uniform gas-liquid distribution in the porous layers of the cell. Engineered cavities or channels may provide pathways for gas to be released preventing large regions to be occupied by gas. This may avoid generation of hot spots and may advantageously provide a more uniform temperature distribution across the cell.

[0080] FIGS. 7B and 7C depict additional, alternative example of a porous layer having a plurality of channels. In these particular examples, the plurality of channels does not extend through the entire depth of the porous layer. Instead, the channels extend a certain distance less than the entire depth of the porous layer. The average depth of the channels may be at least 50%, at least 60%, at least 70%, at least 80%, at least 90% of the overall depth/thickness of the porous layer, or in a range of 50-99%, in a range of 60-99%, in a range of 70-99%, or in a range of 80-99% of the entire depth/thickness of the porous layer. Alternatively, the average depth of the channels may be a distance of at least 500 microns, at least 300 microns, at least 150 microns, at least 50 microns, at least 10 microns, in a range of 10-500 microns, in a range of 10-300 microns, in a range of 10-150 microns, or in a range of 10-50 microns, wherein the depth of each channel remains less than the entire depth or thickness of the porous layer.

[0081] In contrast to different depth dimensions, similar channel widths/diameters, numbers of channels, positioning of channels, shapes of channels, and distances between channels may be present in this particular arrangement as described above with reference to FIG. 7A.

[0082] In certain examples, the openings of the channels extending partially through the porous layer may be positioned adjacent to the membrane of the electrochemical cell, wherein the opposite surface having no surface channels is positioned adjacent to the flow field. Alternatively, the openings of the channels may be positioned adjacent to the flow field of the electrochemical cell, wherein the opposite surface is positioned adjacent to the membrane. As depicted in FIG. 7B, a microporous layer (MPL) is positioned on one side of the porous layer, covering one end of the plurality of channels within the overall porous layer. As depicted in FIG. 7C, a microporous layer is positioned on both sides of the porous layer. The presence of a MPL on one or both sides may provide advantageous performance aspects over a porous layer having channels extending through the entire depth of the layer through a more restricted flow of fluids through the porous layer, as no direct channel from one surface of the layer to the opposing surface of the layer is present. The thickness of each MPL is also configurable. In certain examples, the thickness of the MPL is less than 25% of the overall thickness of the porous layer, less than 20%, less than 15%, less than 10%, less than 5%, less than 1%, in a range of 1-25%, or in a range of 1-10% of the overall thickness of the porous layer. Alternatively, the thickness of the MPL is less than 20 microns, less than 10 microns, less

than 5 microns, less than 1 micron, in a range of 0.1-20 microns, or in a range of 0.1-10 microns.

[0083] The direction or orientation of the channels within the porous layer may also be configurable. In certain examples discussed in greater detail below (e.g., via the use of a solvent exchange bath process), the channels may be oriented in a direction parallel to each other (such as depicted in FIGS. 7A-7C).

[0084] Alternatively, in other examples discussed in greater detail below (e.g., via the use of an electrospinning process), the channel orientations may be positioned in different directions within the same porous layer. For example, the porous layer may be patterned such that in one region the channels have an orientation of +30 degrees from the shortest distance between the faces, in another region 0 degrees, and in another -30 degrees. These different orientations may be advantageous for similar reasons identified within this disclosure for facilitating fluid transport through the porous layer.

[0085] FIG. 7D depicts an example of an arrangement of channel orientations with different directions/orientations. In this particular example, the porous layer is positioned between a flow field and a membrane. The plurality of channels within the porous layer has different orientations that advantageously spread out and contact a more disperse area of the membrane on one end of the porous layer, while being directed to a more specific area at the flow field channels at the opposite end of the porous layer.

[0086] FIG. 8 depicts various examples of different shapes and sizes of channels. Specifically, in the left column of FIG. 8, various examples are shown for channels not extending through the entire depth/thickness of the porous layer (such as in FIGS. 7B and 7C). In the right column of FIG. 8, various examples are shown for channels extending through the entire depth (such as in FIG. 7A). As noted above, the shapes and sizes of the channels within the porous layer may be configurable. The shapes and sizes of the channels may advantageously provide voids or cavities large enough to allow gas bubbles to flow therethrough without being trapped. The channels may have semispherical shapes, conical shapes, cylindrical shapes, frustoconical shapes, tetrahedron shapes, pyramid shapes, prolate spheroid shapes, or the like. The various examples in FIG. 8 represent certain embodiments of these various shapes. Additionally, each of the channels may have a side cross-sectional shape and a top cross-sectional shape. The channels may have a side cross-sectional shape and/or a top cross-sectional shape of a pentagon, rectangle, square, triangle, circle, oval, trapezoid, or the like. The shapes and/or sizes of the channels are not limited to those depicted in FIG. 8 and described herein.

[0087] FIG. 9A depicts an additional example of such a porous layer (e.g., PTL or GDL) having a plurality of open channels or cavities within the layer. In this particular example, the plurality of channels extends through the entire depth of the porous layer (similar to FIG. 7A). The channels may be configured to be parallel to each other. Further, unlike the example in FIG. 7A, the parallel channels in the example in FIG. 9A may be oriented in a direction that is not perpendicular to the plane in which the porous layer is positioned. Specifically, the channels may be positioned at an angle between 0-90°, between 0-45°, between 0-60°, between 30-90°, between 30-60°, between 45-90°, or between 60-90°, wherein the angle is defined between an axis extending through a center of a channel of the plurality

of channels and a plane of a membrane of the electrochemical cell. In this arrangement, the channel may advantageously provide a more tortuous path or non-direct path between adjacent layers within the electrochemical cell (e.g., the flow field and membrane layers). This may aid in providing a better fluid flow arrangement of reactants toward the membrane and product gases and unreacted water toward the flow field.

[0088] In contrast to a different orientation, similar channel widths/diameters, numbers of channels, positioning of channels, shapes/sizes of channels, and distances between channels may be present in this particular arrangement as described above with reference to FIG. 7A.

[0089] FIGS. 9B and 9C depict additional, alternative examples of a porous layer having a plurality of channels. In these particular examples, the plurality of channels is oriented at an angle (similar to the example in FIG. 9A) and also do not extend through the entire depth of the porous layer (similar to the example in FIGS. 7B and 7C). As depicted in FIG. 9B, a microporous layer (MPL) is positioned on one side of the porous layer, covering one end of the plurality of channels within the overall porous layer. As depicted in FIG. 9C, a microporous layer is positioned on both sides of the porous layer. In these examples, the channels extend a certain distance less than the entire depth of the porous layer. Similar to the examples discussed above in FIGS. 7B and 7C, the average depth of the channels may be at least 50%, at least 60%, at least 70%, at least 80%, at least 90% of the overall depth/thickness of the porous layer, or in a range of 50-99%, in a range of 60-99%, in a range of 70-99%, or in a range of 80-99% of the entire depth/thickness of the porous layer. Alternatively, the average depth of the channels may be a distance of at least 500 microns, at least 300 microns, at least 150 microns, at least 50 microns, at least 10 microns, in a range of 10-500 microns, in a range of 10-300 microns, in a range of 10-150 microns, or in a range of 10-50 microns, wherein the depth of each channel remains less than the entire depth or thickness of the porous layer.

[0090] In contrast to different depth dimensions and a different orientation, similar channel widths/diameters, numbers of channels, positioning of channels, shapes of channels, and distances between channels may be present in this particular arrangement as described above with reference to FIG. 7A.

[0091] FIGS. 10A and 10B depict additional examples of a porous layer (e.g., PTL or GDL) having a plurality of open channels or cavities within the layer. In these particular examples, the plurality of channels may include a coating composition covering the internal surface of each channel. The presence of the coating composition on the walls of the channels may provide one or more performance advantages for the porous layer during the operation of the electrochemical cell. For example, the coating composition may advantageously provide or improve an overall corrosion resistance of the porous layer. Further, the inclusion of the coating composition on the walls of the channels may reduce or eliminate a need to include any additional coating or filler composition within the remainder of the porous layer composition, therein advantageously reducing an overall amount of coating or filler composition within the porous layer formulation.

[0092] The coating may be an oxidation-resistant metal such as, but not limited to, Pt, Au, Ti, Cr, Si, Zr, Y, Nb, and/or

Al. In one particular example, the coating may include Pt nanoparticles or sintered Pt. Such an oxidation-resistant metal may be particularly advantageous in limiting corrosion on the anode side of the cell from the oxygen generated in the water-splitting reaction. Alternative metal compositions may include TiC, TiN, TiB₂ particles, and so on. These metals or metal composition may be advantageously included within the porous layer (e.g., PTL) composition to adjust/improve through-plate resistivity, porosity, contact resistance, or other electrochemical aspects of the PTL.

[0093] The thickness of the coating layer on the channel walls may be configurable. Based on the particle size of the coating composition, one or more layers of coating particles may be applied to the channel wall surface during formation of the porous layer. In certain examples, the particle size of the coating composition is less than 10 microns, less than 5 microns, less than 1 micron, less than 100 nm, less than 10 nm, or in a range of 1-1000 nm. As such, the thickness of the channel wall may be 10 microns, less than 5 microns, less than 1 micron, less than 100 nm, less than 10 nm, or in a range of 1-1000 nm.

[0094] Methods of formation of such a porous layer are described in greater detail below, specifically with regards to the examples in FIGS. 15 and 16.

[0095] As depicted in FIG. 10A, the plurality of channels may extend through the entire depth of the porous layer and may be oriented in a direction perpendicular to the plane in which the porous layer is positioned (such as the example in FIG. 7A).

[0096] As depicted in FIG. 10B, the plurality of channels may extend through the entire depth of the porous layer and may be oriented in a direction that is not perpendicular to the plane in which the porous layer is positioned (such as the example in FIG. 9A).

[0097] Further, while not depicted, in certain examples, the plurality of channels may not extend through the entire depth of the porous layer (such as the examples in FIGS. 7B, 7C, 9B, and 9C).

[0098] Additionally, the examples depicted in FIGS. 10A and 10B may have similar channel widths/diameters, numbers of channels, positioning of channels, shapes of channels, and distances between channels as described above with reference to FIG. 7A.

Methods of Manufacturing Porous Layers

[0099] Described hereinafter are methods of manufacturing a porous layer having a plurality of channels according to embodiments of the present disclosure. Any one of the porous layer embodiments described above may be manufactured using the methods described below.

[0100] FIG. 11 depicts one example of forming a porous layer having a plurality of channels.

[0101] In a first act of the manufacturing method, the method may include forming or providing a slurry or suspension including: (1) a base component of the porous layer; (2) a solvent; and (3) optionally one or more binders or additive components. The metal/base composition and optional additives may be stirred or mixed within the solvent to create a disperse, uniform slurry composition.

[0102] The amount of each component (i.e., wt. % or vol % of each component) may be configurable. For example, adjustments to the amount of base component, solvent, and additives within the slurry may target a desired channel design or porous layer density. That is, an increase in the

amount of solvent within the slurry composition may lead to an increase in the number of channels or width of channel openings.

[0103] In certain examples, this base component within the slurry may include a metal powder or metal fiber/felt. The metal may include a titanium (Ti) powder or Ti fiber/felt. In certain examples, the metal powder may additionally or alternatively include an oxidation-resistant material such as, but not limited to, platinum (Pt), gold (Au), chromium (Cr), silicon (Si), zirconium (Zr), yttrium (Y), niobium (Nb), and/or aluminum (Al). This oxidation-resistant metal may be particularly advantageous in limiting corrosion in an oxygen environment on the anode side of the cell. Alternative metal powders may include titanium carbide (TiC), titanium nitride (TiN), titanium diboride (TiB₂), or combinations thereof. In certain examples, the metal powder may include one or more organic additives.

[0104] The particle size of the metal powder in the slurry may be configurable for the desired density of the porous layer. Specifically, the particle size of the metal powder may advantageously affect channel size or pores per unit area within the layer. In certain examples, the average particle size of the component(s) within the metal powder (e.g., Ti powder) may be less than 50 microns, less than 30 microns, less than 20 microns, less than 10 microns, less than 5 microns, less than 1 micron, in a range of 1-50 microns, in a range of 1-20 microns, in a range of 1-10 microns, or in a range of 1-5 microns.

[0105] The solvent within the slurry composition may also be configurable to control or affect the channel size or density of pores. In certain examples, the solvent within the slurry composition is a low-density solvent. Non-limiting examples of low-density solvents may include deep eutectic solvents (DESSs), supramolecular solvents (SUPRAs), and switchable hydrophobicity solvents (SHSs).

[0106] In certain examples, the composition of the slurry includes at least 20 vol % solvent, at least 30 vol % solvent, at least 40 vol % solvent, at least 50 vol % solvent, at least 60 vol % solvent, at least 70 vol % solvent, at least 80 vol % solvent, in a range of 20-80 vol % solvent, in a range of 30-70 vol % solvent, or in a range of 40-60 vol % solvent.

[0107] As noted above, in certain examples, the slurry may additionally include one or more additives or binders. A binder may advantageously be included within the slurry composition to assist in binding the metal powder particles together following the removal of the solvent. The binder composition may be any material configured to bind and coat the metal composition, such as a plastic or paraffin composition (e.g., polyvinyl butyral). The percentage or concentration of binder in the overall starting composition is variable (e.g., 10-90 wt. %, 20-80 wt. %, 30-70 wt. %, or 40-60 wt. %). The binder may be chosen for removal in air, vacuum, or otherwise inert environment at low enough temperature to not induce embrittlement of Ti from O or N uptake (e.g., 350° C.). In other examples, the binder may be chosen to be any binder composition that is immiscible in a non-solvent solution (as discussed below during the solvent exchange process).

[0108] In other examples, an additive may be a filler composition. In certain examples, the filler composition may advantageously provide or improve an overall corrosion resistance of the porous layer. The filler may include an oxidation-resistant metal such as, but not limited to, Pt, Au, Ti, Cr, Si, Zr, Y, Nb, and/or Al. This oxidation-resistant metal

may be particularly advantageous in limiting corrosion on the anode side of the cell from the oxygen generated in the water-splitting reaction. Alternative metal compositions may include TiC, TiN, TiB₂ particles, and so on. These metals or metal composition may be advantageously included within the porous layer (e.g., PTL) composition to adjust/improve through-plate resistivity, porosity, contact resistance, or other electrochemical aspects of the PTL.

[0109] Subsequently, in a second act following the providing or forming of the slurry, as shown in FIG. 11, the slurry may be cast or applied onto a substrate to form a green state wet tape on the substrate. As used herein, “green state” may refer to a composition or structure that has not undergone heat treatment (e.g., sintering) to form a solid and/or porous mass. As used herein, the term “wet tape” may refer to a composition that has not been dried or in which at least a portion of the solvent within the slurry composition has not evaporated.

[0110] The type of substrate may be any known substrate used in the art. In certain examples, the substrate may be a composition that is permeable to the non-solvent solution in the solvent exchange process discussed in greater detail below (which may advantageously allow for a solvent exchange to occur through pores or openings within the substrate itself).

[0111] In certain embodiments, any known method may be used to cast, pour, or apply the slurry to the surface of the substrate. For example, the slurry may be tape cast or dip coated, onto the substrate. A tape casting or doctor blading process advantageously allows the thickness and porosity of the porous layer to be fine-tuned or adjusted to meet certain parameters. Specifically, the tape casting or doctor blading process is advantageous in optimizing a porous layer's gradient structure and the pore structure's orientation. For example, the shape (e.g., cylindrical), size, and direction of the particle may be manipulated. Therefore, the process is particularly suited to manufacturing thin, porous transport layers for PEM electrolyzers.

[0112] In certain examples, a doctor blade may be used to selectively change a thickness of the slurry cast on to the surface to a desired level. The thickness of the slurry cast onto the substrate may correspond to a desired thickness of the porous layer. As noted above, the thickness or depth of the porous layer, (e.g., a PTL or GDL) may be in a range of 1-1000 microns, 1-100 microns, 10-100 microns, 10-1000 microns, or 100-1000 microns, for example. In certain examples, smaller metal powder particles may allow for a denser and thinner layer, allowing for the casting process to apply a thinner slurry to the substrate than may be seen in the current state of the art.

[0113] In certain examples, following the casting of the slurry onto the substrate, a portion but not all of the solvent within the slurry may evaporate. This may be a fixed interval of time (i.e., the evaporation time) to control the amount of evaporation prior to the next act within the manufacturing process.

[0114] As shown in FIG. 11, in a third act of the method, the wet tape and substrate are submerged into a bath having a non-solvent solution. In this particular example, the wet tape and substrate are submerged in an orientation in which the plane of the substrate is parallel with the plane of the bath solution. During the submersion within the bath, a directional exchange takes place in which a portion of the solvent composition within the wet tape is removed from the wet

tape via interaction with the non-solvent solution within the bath to form a wet tape having a plurality of parallel channels. In this particular example, due to the orientation of the wet tape and substrate within the bath, the orientation of the formed channels is perpendicular to the plane of the substrate.

[0115] In certain examples, the non-solvent may be any composition that is at least partially immiscible with the solvent (and any binder present in the slurry composition) and has a greater density than the solvent at the temperature of the bath. For example, the non-solvent may include methylethylketone and water or any acetate and water (e.g., ethyl acetate, propylacetate). The relatively low density of the solvent compared to the non-solvent advantageously results in a directional solvent exchange when the wet tape is immersed in the bath. In certain examples, this exchange occurs on the free side of the wet tape facing away from the substrate. (In alternative examples, in the case of a porous or permeable substrate, the exchange may occur on the ‘closed’ side of the wet tape abutting the substrate.) In either scenario, the directional exchange between the solvent and nonsolvent advantageously creates the directionally aligned/parallel channels extending through the porous layer.

[0116] The operating parameters for the bath are configurable. Specifically, the temperature of the bath may be a temperature at which the density of the non-solvent is greater than the density of the solvent within the wet tape/slurry composition. Additionally, the time that the wet tape is submerged within the bath is configurable. For example, the submersion time may be a minimum time needed for the directional exchange of solvent and non-solvent to form channels running through the entire depth/thickness of the wet tape. Alternatively, the submersion time may be a fixed time known to generate a fixed channel depth less than the entire depth of the wet tape (which could be learned through experimentation).

[0117] Additionally, in certain examples, a filler composition may be added to bath containing the non-solvent in order to deposit the filler onto the channel walls and surface faces of the porous layer during the solvent-exchange step. In certain examples, the filler composition may advantageously provide or improve an overall corrosion resistance of the porous layer. The filler may include an oxidation-resistant metal such as, but not limited to, Pt, Au, Ti, Cr, Si, Zr, Y, Nb, and/or Al. This oxidation-resistant metal may be particularly advantageous in limiting corrosion on the anode side of the cell from the oxygen generated in the water-splitting reaction. Alternative metal compositions may include TiC, TiN, TiB₂ particles, and so on. These metals or metal composition may be advantageously included within the porous layer (e.g., PTL) composition to adjust/improve through-plate resistivity, porosity, contact resistance, or other electrochemical aspects of the PTL.

[0118] As shown in FIG. 11, in a fourth act of the method, following the submerging into the bath and formation of the channels during the exchange time period within the bath, the wet tape having the plurality of channels is removed from the bath. At this stage, the wet tape is dried, wherein further solvent within the wet tape is configured to evaporate to form a green tape having a plurality of channels. The drying process may be conducted under ambient room temperature conditions (e.g., 20-25° C.). Alternatively, a room or environment (e.g., drying oven) having an elevated

temperature greater than 25° C. may be used to expedite the drying process and formation of the green tape.

[0119] Finally, in a fifth act of the method, the green tape having the plurality of channels may be sintered to form the porous layer (i.e., a brown tape) for use within the electrochemical cell. This process may take place prior to or subsequent to the removal of the substrate from the green tape.

[0120] In one particular example, any substrates may be removed prior to sintering. Subsequent to removal of the substrate, the green tape may be sintered to form the porous layer for inclusion within the electrochemical cell in which the porous layer is positioned between the membrane and a flow field of the cell.

[0121] Alternatively, in certain examples, the green tape may be positioned adjacent to the flow field within the electrochemical cell and subsequently sintered. In this alternative process, the green tape and flow field are sintered together to advantageously create a monolithic flow field/porous layer interface.

[0122] The sintering process may involve any known sintering process in the art. For example, the green tape may include titanium (Ti) and have a sintering temperature in the range of 800° C. to 1100°. During this process, the green state starting composition (e.g., metal powder) is heated to coalesce the starting composition into a solid or porous mass without liquefaction, (e.g., heating the starting composition to a temperature below the melting point of a compound within the starting composition—such as a temperature below the melting point of titanium). Further, to the extent the substrate remains attached to the green tape during the sintering process, the sintering temperature should be set at a temperature that is capable of conducting the sintering of the titanium powder, for example, without adversely affecting the properties of the substrate (i.e., melting the substrate). After sintering, the substrate (if present) may be removed, and a chemical etching may be performed to remove any substrate material that remains present within the porous layer without affecting the porous layer. For example, hydrochloric acid, nitric acid, or sulfuric acid may be used to etch the remaining substrate without affecting a titanium structure of the porous layer.

[0123] FIGS. 12A and 12B depict additional examples of forming a porous layer having a plurality of channels. The process is similar to the example discussed above for FIG. 11, and as such, will not be repeated in its entirety. A main difference in these particular examples takes place on the front end of the formation method. Specifically, following the formation of the slurry and the casting or application of the slurry to the substrate to form a wet tape on the substrate, the wet tape is held on the substrate for a longer period of time than the process in FIG. 11. As such, one or more surfaces of the wet tape begin to dry as solvent is evaporated, wherein a skin or microporous layer may be formed on the exposed surface of the wet tape and/or the surface of the wet tape positioned adjacent to the substrate prior to insertion into the bath. This skin formation may affect the solvent exchange process, wherein the channels may not necessarily extend through the entire depth of the porous layer. FIG. 12A depicts an example in which only the exposed surface has formed a skin or microporous layer. FIG. 12B depicts an example in which only both surfaces of the wet tape have formed skins or microporous layers prior to insertion into the bath. These examples may provide advantageous per-

formance aspects over a porous layer having channels extending through the entire depth of the layer through a more restricted flow of fluids through the porous layer, as no direct channel from one surface of the layer to the opposing surface of the layer is present.

[0124] FIG. 13 depicts a further example of forming a porous layer having a plurality of channels. Again, the process is similar to the example discussed above for FIG. 11, and as such, will not be repeated in its entirety. A main difference in this particular example takes place during the submersion within the bath. Specifically, following the formation of the slurry and the casting or application of the slurry to the substrate to form a wet tape on the substrate, the wet tape and substrate are submerged within the bath at an angle in which the plane of the substrate is not parallel with the plane of the bath solution. In this particular example, due to the orientation of the wet tape and substrate within the bath, the orientation of the formed channels is not perpendicular to the plane of the substrate. Instead, the channels may be oriented in a direction that is not perpendicular to the plane in which the porous layer and substrate are positioned. Specifically, the channels may be positioned at an angle between 0-90°, between 0-45°, between 0-60°, between 30-90°, between 30-60°, between 45-90°, or between 60-90°, as described above with reference to FIG. 7B.

[0125] FIG. 14 depicts an additional example of forming a porous layer having a plurality of channels. The process is similar to the examples discussed above for FIGS. 11-13, and as such, will not be repeated in its entirety. In this example, the porous layer formation process incorporates the features within the examples of FIGS. 12A, 12B, and 13. Specifically, the differences between the example described in detail for FIG. 11 include both main differences described above in FIGS. 12A, 12B, and 13. That is, following the formation of the slurry and the casting or application of the slurry to the substrate to form a wet tape on the substrate, the wet tape is held on the substrate for a longer period of time than the process in FIG. 11, such that a skin or microporous layer may develop on one or both surfaces of the wet tape. While FIG. 14 depicts a skin formation on the exposed surface of the wet tape, similar to that of FIG. 12A, a skin or microporous layer may be formed on both surfaces, such as depicted in FIG. 12B. Additionally, the wet tape and substrate are submerged within the bath at an angle in which the plane of the substrate is not parallel with the plane of the bath solution. Due to the orientation of the wet tape and substrate within the bath and the skin formation on at least one surface of the wet tape, the orientation of the formed channels is not perpendicular to the plane of the substrate and the formed channels do not extend through the entire depth of the porous layer. Instead, the channels may be oriented in a direction that is not perpendicular to the plane in which the porous layer and substrate are positioned. Specifically, the channels may be positioned at an angle between 0-90°, between 0-45°, between 0-60°, between 30-90°, between 30-60°, between 45-90°, or between 60-90°, as described above with reference to FIG. 7B.

[0126] FIG. 15 depicts an additional example of forming a porous layer having a plurality of channels. Again, the process is similar to the example discussed above for FIG. 11, and as such, will not be repeated in its entirety. A main difference in this particular example takes place during the submersion within the bath. Specifically, following the formation of the slurry and the casting or application of the

slurry to the substrate to form a wet tape on the substrate, the wet tape and substrate are submerged within a bath having a different solution composition than described with reference to FIG. 11. For example, in addition to the presence of a non-solvent within the bath solution, the solution also includes a filler composition. In this example, in the exchange process, the solvent within the wet tape is removed from the wet tape in an exchange with the non-solvent to form the plurality of channels, as described above. Further, the filler composition within the solution is configured to coat the channel walls with one or more layers of filler prior to removal of the wet tape from the bath. The thickness or number of layers of filler within the channels may be configurable based on the particle sizes of the filler composition as well as the amount of filler added to the bath solution.

[0127] This presence of the filler composition coating the walls of the channels may provide one or more performance advantages for the porous layer during the operation of the electrochemical cell. For example, the filler composition may advantageously provide or improve an overall corrosion resistance of the porous layer. Further, the inclusion of the filler at this stage of the formulation of the porous layer may position a larger concentration of a corrosion resistant composition within the fluid flow pathways of the porous layer (i.e., the channels). This may advantageously allow for an overall reduced amount of filler composition within the porous layer formulation. That is, less or no filler may be required to be added in the slurry mixture, instead limiting the filler addition to the bath solution.

[0128] The filler may be an oxidation-resistant metal such as, but not limited to, Pt, Au, Ti, Cr, Si, Zr, Y, Nb, and/or Al. In one particular example, the filler composition may include Pt nanoparticles or sintered Pt. Such an oxidation-resistant metal may be particularly advantageous in limiting corrosion on the anode side of the cell from the oxygen generated in the water-splitting reaction. Alternative metal compositions may include TiC, TiN, TiB₂ particles, and so on. These metals or metal composition may be advantageously included within the porous layer (e.g., PTL) composition to adjust/improve through-plate resistivity, porosity, contact resistance, or other electrochemical aspects of the PTL.

[0129] Subsequently, the wet tape with coated channels is allowed to dry and undergo a sintering process similar to the process described above with reference to FIG. 11. The temperature of the sintering process should be set such that the filler composition is not adversely affected (e.g., melted) in the process.

[0130] In certain examples, following the sintering process described herein, the filler composition may undergo further processing or treatment to provide contact resistance and reduce inert platinum group metals or function as an anode catalyst, therein making PTL a porous transport electrode layer.

[0131] FIG. 16 depicts an additional example of forming a porous layer having a plurality of channels. Again, the process is similar to the example discussed above for FIGS. 11 and 15, and as such, will not be repeated in its entirety. A main difference in this particular example takes place during the submersion within the bath. Specifically, following the formation of the slurry and the casting or application of the slurry to the substrate to form a wet tape on the substrate, the wet tape and substrate are submerged within

the bath having the non-solvent and filler at an angle in which the plane of the substrate is not parallel with the plane of the bath solution. In this particular example, due to the orientation of the wet tape and substrate within the bath, the orientation of the formed coated channels is not perpendicular to the plane of the substrate. Instead, the channels may be oriented in a direction that is not perpendicular to the plane in which the porous layer and substrate are positioned. Specifically, the channels may be positioned at an angle between 0-90°, between 0-45°, between 0-60°, between 30-90°, between 30-60°, between 45-90°, or between 60-90°, as described above with reference to FIG. 7B.

[0132] In certain alternative examples, the formation of a porous layer with a plurality of channels may take place without the insertion of a wet tape into a solvent bath, as described above in the examples for FIGS. 11-16.

[0133] Instead, the plurality of channels in the porous layer may be formed via an electrospinning technique. In this formulation, the method may include a first act of forming or providing a composition having: (1) a base component of the porous layer; (2) optionally one or more solvents, and (3) optionally one or more binders or additive components. The metal/base composition and optional additives may be stirred or mixed within the optional solvent to create a disperse, uniform slurry composition.

[0134] As discussed above in the examples for FIGS. 11-16, the amount of each component (i.e., wt. % or vol % of each component), the composition formulation and the particle sizes may be configurable and may be applicable in these embodiments as well.

[0135] In the second act following the providing or forming of the slurry, the slurry may be infiltrated into a fibrous mat and subsequently allowed to dry to form a green state tape together with the fibrous mat. Additionally, an excess of slurry may be applied such that the fibrous mat is not only saturated, but a layer of slurry may uniformly coat one or both sides of the fibrous mat.

[0136] The fibrous mat composition may be chosen for removal in air, vacuum, or otherwise inert environment at low enough temperature so as to not induce embrittlement of Ti from O or N uptake (e.g., 350° C.). In other examples, the fiber material may be chosen to be any composition that is immiscible in the slurry.

[0137] The fibrous mat may include microfibers or nanofibers that are patterned such that they may have one or more orientations. The fibrous mat may be prepared by melt spinning, dry spinning, wet spinning, gel spinning, liquid crystal spinning, dispersion spinning, reactive spinning, electrospinning, or any other method of preparing polymer fibers known in the art.

[0138] In certain embodiments, the substrates onto which the fibers are deposited during spinning may be patterned such that they may have varying degrees of hydrophilicity or conductivity to give rise to the preferential orientations of the fibers. Within the given spinning system, any jets, nozzles, needles, spinarets, collectors, auxiliary electrodes, and substrates may be configured. Further, any jets, nozzle, needles, spinarets, or other depositing mechanisms may be customized to provide the desired configuration of channels and micropores. Additionally, any other known parameters or settings relevant to the chosen method may be configured.

[0139] In certain examples, a filler composition may be deposited onto the fibrous mat before addition of the slurry in order to deposit the filler onto the channel walls of the

porous layer. In certain examples, the filler composition may advantageously provide or improve an overall corrosion resistance of the porous layer. The filler may include an oxidation-resistant metal such as, but not limited to, Pt, Au, Ti, Cr, Si, Zr, Y, Nb, and/or Al. This oxidation-resistant metal may be particularly advantageous in limiting corrosion on the anode side of the cell from the oxygen generated in the water-splitting reaction. Alternative metal compositions may include TiC, TiN, TiB₂ particles, and so on. These metals or metal composition may be advantageously included within the porous layer (e.g., PTL) composition to adjust/improve through-plate resistivity, porosity, contact resistance, or other electrochemical aspects of the PTL.

[0140] In certain embodiments, any known method or methods may be used to deposit, infiltrate, or cast the filler solution or slurry into or onto the fibrous mat. For example, the slurry may be infiltrated into the fibrous mat using tape casting, slip casting, or pressurized slip casting. A pressurized slip casting process advantageously allows air and excess liquid to escape from the green state tape, resulting in reduced pore density outside of the channels in the porous layer. A tape-casting process advantageously allows for a thin, uniform coating of the slurry onto one or both sides of the infiltrated fibrous mat.

[0141] In a third act of this method, the green tape having the plurality of channels and fibrous mat may be sintered to form the porous layer (i.e., a brown tape) for use within the electrochemical cell.

[0142] Alternatively, in certain examples, the green tape and fibrous mat may be positioned adjacent to the flow field within the electrochemical cell and subsequently sintered. In this alternative process, the green tape and flow field are sintered together to advantageously create a monolithic flow field/porous layer interface.

[0143] The sintering process may involve any known sintering process in the art. For example, the green tape may include titanium (Ti) and have a sintering temperature in the range of 800° C. to 1100°. During this process, the green state starting composition (e.g., metal powder) is heated to coalesce the starting composition into a solid or porous mass without liquefaction, (e.g., heating the starting composition to a temperature below the melting point of a compound within the starting composition—such as a temperature below the melting point of titanium). Further, to the extent the substrate remains attached to the green tape during the sintering process, the sintering temperature should be set at a temperature that is capable of conducting the sintering of the titanium powder, for example, without adversely affecting the properties of the substrate (i.e., melting the substrate). After sintering, the substrate (if present) may be removed, and a chemical etching may be performed to remove any substrate material that remains present within the porous layer without affecting the porous layer. For example, hydrochloric acid, nitric acid, or sulfuric acid may be used to etch the remaining substrate without affecting a titanium structure of the porous layer.

[0144] One or more embodiments of the disclosure may be referred to herein, individually and/or collectively, by the term “invention” merely for convenience and without intending to voluntarily limit the scope of this application to any particular invention or inventive concept. Moreover, although specific embodiments have been illustrated and described herein, it should be appreciated that any subsequent arrangement designed to achieve the same or similar

purpose may be substituted for the specific embodiments shown. This disclosure is intended to cover any and all subsequent adaptations or variations of various embodiments. Combinations of the above embodiments, and other embodiments not specifically described herein, are apparent to those of skill in the art upon reviewing the description.

[0145] As used herein, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

[0146] As used herein, “for example,” “for instance,” “such as,” or “including” are meant to introduce examples that further clarify more general subject matter. Unless otherwise expressly indicated, such examples are provided only as an aid for understanding embodiments illustrated in the present disclosure and are not meant to be limiting in any fashion. Nor do these phrases indicate any kind of preference for the disclosed embodiment.

[0147] The Abstract of the Disclosure is provided to comply with 37 C.F.R. § 1.72(b) and is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing Detailed Description, various features may be grouped together or described in a single embodiment for the purpose of streamlining the disclosure. This disclosure is not to be interpreted as reflecting an intention that the claimed embodiments require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter may be directed to less than all of the features of any of the disclosed embodiments. Thus, the following claims are incorporated into the Detailed Description, with each claim standing on its own as defining separately claimed subject matter.

[0148] It is intended that the foregoing detailed description be regarded as illustrative rather than limiting and that it is understood that the following claims including all equivalents are intended to define the scope of the disclosure. The claims should not be read as limited to the described order or elements unless stated to that effect. Therefore, all embodiments that come within the scope and spirit of the following claims and equivalents thereto are claimed as the disclosure.

1. A porous layer of an electrochemical cell, the porous layer comprising:

- a porous composition having a plurality of micropores; and
- a plurality of channels having opening diameters that are larger than an average pore diameter of the plurality of micropores,

wherein the plurality of channels extends through at least 50% of a depth of the porous layer as measured in a direction perpendicular to a plane in which the porous layer is oriented,

wherein the porous layer is configured to convey a two-phase mixture of liquid and gas within the electrochemical cell, and

wherein each channel of the plurality of channels is configured to facilitate a transfer of gas from the porous layer into an adjacent flow field of the electrochemical cell.

2. The porous layer of claim 1, wherein the porous layer is a porous transport layer (PTL) configured to be positioned between a membrane and an anode flow field of the electrochemical cell.

3. The porous layer of claim 2, wherein the porous composition comprises a titanium porous sintered powder composition, a titanium mesh composition, a titanium fiber felt composition, or a combination thereof.

4. The porous layer of claim 1, wherein the porous layer is a gas diffusion layer (GDL) configured to be positioned between a membrane and a cathode flow field of the electrochemical cell.

5. The porous layer of claim 4, wherein the porous composition comprises a carbon paper composition, a carbon fiber felt composition, a carbon cloth composition, or a combination thereof.

6. The porous layer of claim 1, wherein the two-phase mixture includes a first flow comprising a liquid flowing away from the flow field toward a membrane of the electrochemical cell and a second flow comprising a gas flowing from the membrane toward the flow field of the electrochemical cell.

7. The porous layer of claim 1, wherein each channel of the plurality of channels extends in a same direction such that the channels of the plurality of channels are parallel with each other.

8. The porous layer of claim 7, wherein an orientation of the plurality of channels within the porous layer is at an angle in a range of 30-90°, and

wherein the angle is defined between an axis extending through a center of a channel of the plurality of channels and a plane of a membrane of the electrochemical cell.

9. The porous layer of claim 1, wherein each channel of the plurality of channels extends through 100% of the depth of the porous layer.

10. The porous layer of claim 1, wherein the porous layer comprises at least one microporous sublayer having no channel of the plurality of channels such that each channel of the plurality of channels extends through less than 100% of the depth of the porous layer, and

wherein the at least one microporous sublayer is positioned on a surface of the porous layer configured to be positioned adjacent to the flow field, on a surface of the porous layer configured to be positioned opposite from the flow field, or on both surfaces of the porous layer.

11. The porous layer of claim 1, wherein an average opening diameter of the plurality of channels is at least ten times greater than an average pore diameter within the porous composition.

12. The porous layer of claim 1, further comprising:
a coating composition positioned on a surface of the plurality of channels.

13. The porous layer of claim 1, wherein a first group of channels of the plurality of channels extend in a first direction when the porous layer is positioned between a membrane and the adjacent flow field of the electrochemical cell, and

wherein at least one second group of channels of the plurality of channels extend in at least one second direction that is different from the first direction when the porous layer is positioned between the membrane and the adjacent flow field.

14. The porous layer of claim 13, wherein the first group of channels and the at least one second group of channels are configured to align with one or more flow field channels of the adjacent flow field.

15. A method of manufacturing a porous layer, the method comprising:

casting a slurry composition having a solvent composition onto a substrate to provide a wet tape on the substrate, wherein the slurry composition comprises a metal powder and the solvent composition;

submerging the wet tape on the substrate into a bath solution having a non-solvent composition, wherein a directional exchange takes place in which a portion of the solvent composition within the wet tape is removed from the wet tape via interaction with the non-solvent composition within the bath solution to form a wet tape having a plurality of parallel channels, wherein the solvent composition of the slurry composition comprises a low density solvent having a lower density than the non-solvent composition within the bath solution;

removing the wet tape having the plurality of parallel channels from the bath solution; and

sintering the wet tape having the plurality of parallel channels to form the porous layer.

16. The method of claim 15, wherein the slurry composition further comprises one or more binders and/or one or more additive compositions.

17. The method of claim 16, wherein the one or more binders comprises a plastic or paraffin composition configured to bind and/or coat the metal powder.

18. The method of claim 16, wherein the one or more additive compositions comprises an oxidation-resistant metal composition configured to provide corrosion resistance within the porous layer, and

wherein the oxidation-resistant metal composition comprises Pt, Au, Ti, Cr, Si, Zr, Y, Nb, Al, TiC, TiN, TiB₂, or combinations thereof.

19. The method of claim 15, wherein the bath solution further comprises a filler composition configured to coat walls of the plurality of parallel channels during or following the directional exchange of the solvent composition and the non-solvent composition.

20. The method of claim 15, wherein the wet tape on the substrate is submerged into the bath solution at an angle in which a plane of the substrate is not parallel with a plane of the bath solution.

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