

## MEMBRANE FRAME FOR ELECTRODEPOSITION TOOL

### BACKGROUND

**[0001]** Electrodeposition can be used in integrated circuit manufacturing processes to deposit electrically conductive films onto substrates. Electrodeposition involves the electrochemical reduction of dissolved ions of a selected metal to an elemental state on a substrate to form a film of the selected metal. Electrodeposition systems comprise a cathode chamber through which a catholyte solution circulates, and an anode chamber through which an anolyte solution circulates. An ion-exchange membrane is positioned between the cathode chamber and anode chamber. The ion-exchange membrane selectively allows some ions to pass from the anolyte to the catholyte while preventing the passage of other ions and organic additives.

### SUMMARY

**[0002]** 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 to limit the scope of the claimed subject matter. Furthermore, the claimed subject matter is not limited to implementations that solve any or all disadvantages noted in any part of this disclosure.

**[0003]** Examples are disclosed that relate to efficiently draining catholyte solution from a volume between a high-resistance virtual anode (HRVA) and an ion-exchange membrane in an electrodeposition system. In one example system, an electrodeposition tool comprises an anode chamber and a cathode chamber. A HRVA is positioned within the cathode chamber. An ion-exchange membrane is positioned between the anode chamber and the cathode chamber. The ion-exchange membrane is supported by a membrane frame. The electrodeposition tool further comprises an aspiration flow path configured to drain a volume between the HRVA and the ion-exchange membrane. The aspiration flow path is defined by the ion-exchange membrane and a groove in the membrane frame.

**[0004]** In some such examples, the groove is formed around at least partially around a perimeter of the membrane frame.

[0005] Additionally or alternatively, in some such examples, the membrane frame comprises an aspiration port in fluid communication with the groove, wherein the aspiration port is in fluid communication with a pump.

[0006] Additionally or alternatively, in some such examples, the membrane frame comprises a baffle that extends toward the HRVA.

[0007] Additionally or alternatively, in some such examples, the groove is formed in the baffle.

[0008] Additionally or alternatively, in some such examples, the baffle comprises a plurality of openings.

[0009] Additionally or alternatively, in some such examples, two or more of the plurality of openings are located on opposite sides of the baffle.

[0010] Additionally or alternatively, in some such examples, the two or more openings are offset along a length of the baffle.

[0011] Additionally or alternatively, in some such examples, the baffle is one of a plurality of baffles that divide the volume between the HRVA and the ion-exchange membrane into a plurality of differently sized volumes, wherein a largest volume is located between a pair of baffles closer to an aspiration port, and wherein a smallest volume is located between a perimeter of the membrane frame and a baffle farther from the aspiration port.

[0012] Additionally or alternatively, in some such examples, the aspiration flow path comprises a tube extending from the membrane frame into the volume between the HRVA and the ion-exchange membrane.

[0013] Another example provides a membrane frame for an electrodeposition tool. The membrane frame comprises a plurality of baffles. Each baffle of the plurality of baffles extends between opposing locations along a perimeter of the membrane frame. The membrane frame comprises a groove formed in one or more of the perimeter of the membrane frame or at least one baffle of the plurality of baffles. The groove is configured to define an aspiration flow path to drain a volume between a HRVA and an ion-exchange membrane when the ion-exchange membrane is positioned on the membrane frame and when the membrane frame is positioned in the electrodeposition tool.

[0014] In some such examples, each baffle comprises a plurality of openings.

[0015] Additionally or alternatively, in some such examples, two or more of the plurality of openings are located on opposite sides of the baffle.

[0016] Additionally or alternatively, in some such examples, the two or more openings are offset along a length of the baffle.

[0017] Additionally or alternatively, in some such examples, the plurality of baffles divide the volume between the HRVA and the ion-exchange membrane into a plurality of differently sized volumes, wherein a largest volume is located between a pair of baffles closer to an aspiration port, and wherein a smallest volume is located between a perimeter of the membrane frame and a baffle farther from the aspiration port.

[0018] Another example provides a method of draining a volume of a catholyte from a volume between a high-resistance virtual anode (HRVA) and an ion-exchange membrane in an electrodeposition tool. The method comprises creating a pressure differential to move the volume of the catholyte through an aspiration port in fluid communication with an aspiration flow path defined by the ion-exchange membrane and a groove in the membrane frame.

[0019] In some such examples, creating the pressure differential to move the volume of the catholyte comprises drawing a vacuum through the aspiration port.

[0020] Additionally or alternatively, in some such examples, moving the volume of the catholyte comprises moving the volume of the catholyte through a portion of the groove formed in a baffle.

[0021] Additionally or alternatively, in some such examples, moving the volume of the catholyte comprises moving at least a portion of the volume of the catholyte through a plurality of openings in the baffle.

[0022] Additionally or alternatively, in some such examples, moving the volume of the catholyte comprises draining a plurality of differently sized volumes formed by a plurality of baffles.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. 1 shows an example electrodeposition tool.

[0024] FIG. 2 shows a schematic top view of an example ion-exchange membrane frame for an electrodeposition tool.

[0025] FIG. 3 shows a schematic bottom view of the ion-exchange membrane frame of FIG. 2.

[0026] FIG. 4 shows a cross-sectional view of the ion-exchange membrane frame of FIGS. 2-3.

[0027] FIG. 5 shows a schematic top view of another example ion-exchange membrane frame for an electrodeposition tool.

[0028] FIG. 6 shows a schematic bottom view of the ion-exchange membrane frame of FIG. 5.

[0029] FIG. 7 shows a cross-sectional view of another example ion-exchange membrane frame for an electrodeposition tool.

[0030] FIG. 8 shows a flow diagram of an example method for draining a volume of a catholyte from a volume between a high-resistance virtual anode (HRVA) and an ion-exchange membrane in an electrodeposition tool.

[0031] FIG. 9 shows a schematic bottom view of another example ion-exchange membrane frame for an electrodeposition tool.

[0032] FIG. 10 shows a schematic bottom view of another example ion-exchange membrane frame for an electrodeposition tool.

#### DETAILED DESCRIPTION

[0033] The term HRVA generally represents a high resistance virtual anode.

[0034] The term “anode” generally represents an electrically conductive structure at which electrochemical oxidation occurs during an electrodeposition process.

[0035] The term “anode chamber” generally represents a physical structure configured to hold at least an anode and anolyte and that provides selective separation from a cathode chamber.

[0036] The term “anolyte” generally represents a solution used in an anode chamber during an electrodeposition process.

[0037] The term “aspiration flow path” generally represents a channel or channels that allow a fluid to egress from a volume.

[0038] The term “aspiration port” generally represents a structure that acts as an exit for fluid to egress from a volume.

[0039] The term “baffle” generally represents a structure that impedes flow of a liquid or solution in a given direction.

[0040] The term “cathode” generally represents a conductive layer on a substrate that is grown during electrodeposition by the electrochemical reduction of ions.

[0041] The term “cathode chamber” generally represents a physical structure configured to hold at least a cathode and catholyte.

[0042] The term “catholyte” generally represents a solution used in a cathode chamber during an electrodeposition process.

[0043] The terms “deposition”, “electrodeposition” and variants thereof generally represents a process in which dissolved ions of one or more metals are reduced on a substrate surface to form a film of the one or more metals.

[0044] The term “electrodeposition system” generally represents a machine configured to perform electrodeposition.

[0045] The term “frame cell” generally represents a void in a membrane frame that exposes an underlying ion-exchange membrane.

[0046] The term “in fluid communication” generally represents a fluid flow path between components.

[0047] The term “groove” generally represents a recess in a membrane frame that can accommodate a fluid flow.

[0048] The term “high-resistance virtual anode” (HRVA) generally represents an ionically resistive structure positioned between a substrate holder and an anode of an electrodeposition tool through which ions flow from the anode to a cathode during electrodeposition. A HRVA approximates a suitably constant and uniform current source in proximity to the cathode.

[0049] The term “ion-exchange membrane” generally represents a semi-permeable membrane that allows the transport of certain dissolved ions, but not other dissolved ions or neutrally charged molecules.

[0050] The term “membrane frame” generally represents a device that supports an ion-exchange membrane.

[0051] The term “perimeter” generally represents an outer boundary of a structure.

[0052] The term “pump” generally represents a device configured to move a fluid.

[0053] The term “substrate” generally represents any object on which a film can be deposited.

[0054] The term “substrate holder” generally represents any structure for supporting a substrate during an electrodeposition process.

[0055] The term “tube” generally represents an elongated structure with a hollow interior configured to conduct a fluid.

[0056] As introduced above, electrodeposition systems comprise a cathode chamber through which a catholyte solution circulates, and an anode chamber through which an anolyte solution circulates. Ions in the catholyte solution are reduced to form

a metal film on a substrate positioned in the cathode chamber. A corresponding oxidation reaction in the anolyte occurs in the anode chamber. An ion-exchange membrane is positioned between the cathode chamber and anode chamber. The ion-exchange membrane selectively allows some ions to pass from the anolyte to the catholyte while preventing the passage of other ions and organic additives.

[0057] An electrodeposition system further can include a high-resistance virtual anode (HRVA). The HRVA is an ionically resistive structure positioned between a substrate holder and an ion-exchange membrane of an electrodeposition tool. The HRVA can approximate a constant and uniform current source in proximity to a cathode of the electrodeposition tool.

[0058] Catholyte and anolyte solutions are often drained from an electrodeposition tool before performing maintenance on the electrodeposition tool. As pumps are used to circulate catholyte and anolyte along respective flow loops, the pumps also can be used to help drain the catholyte solution and the anolyte solution. However, catholyte solution in a volume between the HRVA and the ion-exchange membrane can be difficult to remove. Removing this catholyte solution can requires partial disassembly of the electrodeposition tool. Furthermore, the catholyte solution must be removed manually, for example using a vacuum or a siphon device. This can be time-consuming. Furthermore, flushing the catholyte from this volume can consume a large volume of water.

[0059] Accordingly, examples are disclosed that relate to efficiently draining catholyte from a volume between an HRVA and an ion-exchange membrane. In one example system, an aspiration flow path is configured to drain the volume between the HRVA and the ion-exchange membrane. The aspiration flow path is defined by the ion-exchange membrane and a groove in the membrane frame. The use of a flow path as defined allows catholyte solution to be drained directly from the volume between the HRVA and ion-exchange membrane. In this manner, catholyte solution can be at least partially removed from this volume without requiring any disassembly of the electrodeposition tool.

[0060] FIG. 1 schematically shows a block diagram of an example electrodeposition tool 100. Electrodeposition tool 100 comprises an electrodeposition cell 102 comprising an anode chamber 104 and a cathode chamber 106. Electrodeposition tool 100 further comprises an ion-exchange membrane 108 separating the anode chamber 104 and the cathode chamber 106, and an HRVA 109

within cathode chamber 106. Anode chamber 104 comprises an anode 110. Anode chamber 104 further comprises an anolyte. Cathode chamber 106 comprises a catholyte. The catholyte comprises an ionic species to be deposited on a cathode layer of a substrate 111 as a metal by electrochemical reduction. In some examples, anode 110 comprises a consumable anode formed from the metal being deposited. In other examples, anode 110 comprises an inert anode. Where anode 110 comprises the metal being deposited, electrochemical oxidation of anode 110 at least partially replenishes the ionic species consumed by the electrodeposition process. Bulk anolyte and/or catholyte solutions can be added at times to replenish the ionic species.

**[0061]** Substrate holder 112 is coupled to a substrate holder movement system 113 comprising a lift 114 that is configured to adjust a spacing between substrate holder 112 and HRVA 109. For example, lift 114 can lower substrate holder 112 to position substrate 111 within the catholyte for electrodeposition. Lift 114 further can raise substrate holder 112 from the catholyte after electrodeposition. Substrate holder movement system 113 further can comprise components to control the opening and closing of substrate holder 112.

**[0062]** The catholyte can be circulated between cathode chamber 106 and a catholyte reservoir 120 via a combination of gravity and one or more pumps 122. Likewise, the anolyte can be circulated through anolyte reservoir 124 and anode chamber 104 through a combination of gravity and one or more pumps 126.

**[0063]** The ion-exchange membrane 108 prevents organic species and some ionic species from crossing between cathode chamber 106 and anode chamber 104, while allowing selected ions to cross from anode chamber 104 to cathode chamber 106. As an example, ion-exchange membrane 108 can allow metal ions to cross from anode chamber 104 to cathode chamber 106 for deposition.

**[0064]** The ion-exchange membrane 108 is supported by a membrane frame 128. FIGS. 2-3 show an example membrane frame 200 that can serve as the membrane frame 128 of FIG. 1. FIG. 4 shows a cross-sectional view of the membrane frame 200 along line 4-4 of FIG. 2.

**[0065]** The membrane frame 200 comprises a grid structure 202 comprising a plurality of openings 204 that expose an underlying ion-exchange membrane. The openings 204 may also be referred to as “frame cells” within the membrane frame, to distinguish them from other openings formed in baffles to form a part of an aspiration flow path. Membrane frame 200 also comprises a plurality of baffles 206. Each baffle

206 extends laterally between opposing locations along a perimeter of the membrane frame 200. The baffles 206 extend vertically from the grid structure 202 towards an HRVA. The baffles 206 are arranged in a direction transverse to flow of catholyte across the HRVA, as indicated by arrow 208. The baffles 206 are configured to contact the HRVA. This helps to impede catholyte from flowing through the volume between the HRVA and the ion-exchange membrane. This impedance helps to maintain control of catholyte flow across a substrate during an electrodeposition process. The grid structure of the membrane frame 200 accommodates the positioning of the baffles in a way that can help to avoid disrupting ionic conductivity through the ion-exchange membrane.

**[0066]** The membrane frame 200 can be configured to be used as a replacement part in an existing electrodeposition system. In such examples, the membrane frame 200 can have substantially the same normal projection onto a substrate as the membrane frame being replaced. In this manner, the membrane frame 200 can be substituted for another membrane frame without changing chemistry or methodology used to process a substrate.

**[0067]** As illustrated in FIGS. 3-4, the membrane frame 200 comprises at least one groove 210A, 210B. As described in more detail below, each of the grooves 210A, 210B defines an aspiration flow path configured to drain a volume between an HRVA and an ion-exchange membrane when the ion-exchange membrane is positioned on the membrane frame 200. In other examples, the groove(s) can have any other suitable configuration. For example, and as described in more detail below with reference to FIGS. 4-5, the groove can additionally or alternatively extend around at least a portion of a perimeter of the membrane frame and/or along one or more baffles.

**[0068]** When the ion-exchange membrane is positioned on the membrane frame 200, the groove forms a manifold between the membrane frame 200 and the ion-exchange membrane. This allows aspiration of the volume between the ion-exchange membrane and an HRVA and allows access to separate cavities isolated by the baffles.

**[0069]** In some examples, the membrane frame 200 comprises at least one aspiration port. In the depicted example, two aspiration ports 212A, 212B are shown. The aspiration ports 212A, 212B are in fluid communication with the grooves 210A, 210B, respectively. One or more of the aspiration ports 212A, 212B are in fluid communication with a pump of the electrodeposition tool. For example, the membrane frame 128 of FIG. 1 is in fluid communication with a pump 130. The pump 130 creates

a pressure differential between the membrane frame 128 and an evacuation system 132. In other examples, a pump 130 or other mechanism (e.g. a compressed gas source) can be used provide a positive pressure differential. For example, the pump 130 can pump water (e.g. deionized water) into the electrodeposition cell 102. In this manner, the pump 130 is configured to remove the catholyte from the volume between the ion-exchange membrane 108 and the HRVA 109.

**[0070]** As illustrated in FIG. 4, one or more of the baffles 206 can comprise at least one opening 214. Each opening 214 is configured to permit flow of a catholyte through the baffle. In this manner, the opening(s) 214 and the grooves 210A, 210B together enable aspiration of the volume above the ion-exchange membrane.

**[0071]** In some examples, the opening(s) 214 can be relatively small compared to the baffle 206. Accordingly, catholyte flow through the opening(s) 214 can have a substantially higher impedance than the catholyte solution flow 208 across a substrate. In this manner, the opening(s) 214 can help to maintain a suitably high impedance to catholyte solution flow to avoid disrupting catholyte solution flow 208 across the substrate.

**[0072]** FIGS. 5-6 show another example of a membrane frame 500. The membrane frame 500 can serve as the membrane frame 128 of FIG. 1. Like the membrane frame 200 of FIGS. 2-4, the membrane frame 500 comprises a grid structure 502 comprising a plurality of frame cells 504. The membrane frame 500 also comprises a plurality of baffles 506 and a groove 510. The groove 510 is formed around at least a portion of a perimeter of the grid structure 502.

**[0073]** The membrane frame 500 further comprises a plurality of additional grooves 512A-512D. Each of the additional grooves 512A-512D is formed in one of the baffles 506. Furthermore, each of the additional grooves 512A-512D is in fluid communication with the groove 510 at the perimeter of the grid structure 502. As described in more detail below, the additional grooves 512A-512D further help to aspirate the volume between the HRVA and the ion-exchange membrane.

**[0074]** As illustrated in FIG. 6, one or more of the baffles 506 comprises a pair of openings 514A, 514B. Like the openings 214 in the baffles 206 of FIGS. 2-4, the openings 514A, 514B permit catholyte to flow into groove 512A.

**[0075]** In some examples, the openings 514A, 514B are located on opposite sides of the baffle. Additionally or alternatively, the openings 514A, 514B can be offset along a length of the baffle 506. In this manner, as illustrated in FIG. 6, the openings 514A,

514B are staggered. The staggered openings 514A, 514B impede bulk flow of a catholyte under the HRVA or between the membrane and the HRVA. In this manner, the opening(s) 514A, 514B enable aspiration while maintaining a suitably high impedance to catholyte solution flow to avoid disrupting catholyte solution flow across the substrate.

**[0076]** In the example of FIGS. 5-6, a plurality of baffles 506 divide the volume between the HRVA and the ion-exchange membrane into a plurality of differently sized volumes. Eight volumes formed by the baffles 506 are indicated by brackets 516A-516H in FIG. 5. The volumes 516A and 516B are at least partially bounded by the perimeter of the membrane frame 500 and the groove 512A. The volumes 516C and 516D are at least partially bounded by the perimeter of the membrane frame 500 and the groove 512B. The volumes 516E and 516F are at least partially bounded by the perimeter of the membrane frame 500 and the groove 512C. The volumes 516G and 516H are at least partially bounded by the perimeter of the membrane frame 500 and the groove 512D. Volumes 516D and 516E are larger than volumes 516C and 516F. Volumes 516C and 516F are larger than volumes 516B and 516G. Volumes 516B and 516G are larger than 516A and 516H. Volumes 516D and 516E are located closer to the aspiration port than volumes 516C and 516F. Volumes 516C and 516F are located closer to the aspiration port than volumes 516B and 516G. Volumes 516B and 516G are located closer to the aspiration port than volumes 516A and 516H. Accordingly, the larger volumes can be aspirated at a relatively faster rate than the smaller volumes due to less flow restriction within the aspiration grooves. In this manner, each of plurality of volumes 516A-516H can be drained in substantially the same amount of time.

**[0077]** FIG. 7 shows yet another example of a membrane frame 700. The membrane frame 700 can serve as the membrane frame 128 of FIG. 1. As illustrated in FIG. 7, the membrane frame 700 includes at least one tube 702A, 702B extending from a perimeter of the membrane frame 700. The tubes 702A, 702B can be used in addition to or as an alternative to the grooves 210A, 210B of FIG. 3, the groove 510 of FIG. 6, and/or the grooves 512A-512D of FIG. 6.

**[0078]** Each tube 702A, 702B is in fluid communication with an aspiration port 704A, 704B, respectively. The aspiration ports 704A, 704B can be analogous to the aspiration ports 212A, 212B described above with reference to FIG. 4. In this manner the tubes 702A, 702B can aspirate a volume between an HRVA and ion-exchange membrane.

[0079] In some examples, each tube 702A, 702B is supported by one or more brackets 706A, 706B, respectively. In the example of FIG. 7, the brackets 706A, 706B extend from a membrane-facing surface 708 of the membrane frame 700. The brackets 706A, 706B are configured to stabilize the tubes 702A, 702B. In some examples, the brackets 706A, 706B comprise snap-fit brackets. In other examples, any other suitable type of brackets can be used.

[0080] FIG. 8 shows a flow diagram depicting an example method 800 for draining a volume of a catholyte from a volume between a HRVA and an ion-exchange membrane in an electrodeposition tool. The following description of the method 800 is provided with reference to FIGS. 1-7 above. Method 800 is also applicable to FIGS. 9 and 10, which will be described below. It will be appreciated that the method 800 also can be performed in other contexts.

[0081] At 802, the method 800 comprises creating a pressure differential to move the volume of the catholyte through an aspiration port in fluid communication with an aspiration flow path defined by the ion-exchange membrane and a groove in the membrane frame. In some examples, at 804, creating the pressure differential to move the volume of the catholyte comprises drawing a vacuum through the aspiration port. For example, the pump 130 of FIG. 1 can be used to draw a vacuum in the electrodeposition cell 102. In this manner, the pump 130 can aspirate the volume between the HRVA 109 and the ion-exchange membrane 108. In some examples, water (e.g., deionized water) is supplied to the electrodeposition cell as the catholyte solution is aspirated.

[0082] At 806, in some examples, moving the volume of the catholyte comprises moving the volume of the catholyte through a portion of the groove formed in a baffle. For example, the membrane frame 500 of FIGS. 5-6 comprises additional grooves 512A-512D formed in baffles 506. Each of the additional grooves 512A-512D is in fluid communication with a groove 510 located at a perimeter of the membrane frame 500. In this manner, the catholyte can flow through the additional grooves 512A-512D, through the groove 510, and out of the membrane frame 500.

[0083] In some examples, at 808, wherein moving the volume of the catholyte comprises moving at least a portion of the volume of the catholyte through a plurality of openings in the baffle. For example, the catholyte can flow through openings 214 in the membrane frame 200 of FIGS. 2-4. In the example of FIGS. 5-6, the catholyte can flow through openings 514A, 514B in the membrane frame 500. The openings further

help to drain the catholyte from the volume between the HRVA and the ion-exchange membrane.

**[0084]** At 810, in some examples, moving the volume of the catholyte comprises draining a plurality of differently sized volumes formed by a plurality of baffles. For example, the baffles 506 of FIG. 5 divide the membrane frame 500 into a plurality of differently sized volumes 516A-516H. The larger volumes are located closer to an aspiration port 518 than the smaller volumes. In this manner, each of plurality of volumes 516A-516H can be drained in substantially the same amount of time.

**[0085]** At 812, in some examples, the method optionally further comprises supplying deionized water to the aspiration port to backfill the deionized water into the volume between the ion-exchange membrane and the HRVA. Depending on the structure of the membrane frame, it may in some circumstances be difficult to fully drain the catholyte solution through the aspiration process described above. For instance, some amount of catholyte solution may remain trapped within the volume between the ion-exchange membrane and the HRVA – e.g., in openings or grooves within the membrane frame. Thus, backfilling deionized water (or another suitable liquid) into the aspiration port can beneficially serve to flush remaining catholyte solution from the electrodeposition tool. Deionized water may be supplied to the aspiration port in any suitable way. For instance, the pump 130 may be used to pump deionized water through the aspiration flow path into the electrodeposition tool – e.g., after changing the state of a valve.

**[0086]** FIG. 9 shows another example of a membrane frame 900. The membrane frame 900 can serve as the membrane frame 128 of FIG. 1. Like the membrane frame 200 of FIGS. 2-4, the membrane frame 900 comprises a grid structure 902 comprising a plurality of frame cells 904 that expose an underlying ion-exchange membrane. The membrane frame additionally includes a groove 906. In this example, the groove 906 is a perimeter groove that circumscribes the plurality of frame cells 904. The membrane further includes an intersecting groove 908 that extends between openings in the perimeter groove 906.

**[0087]** Perimeter groove 906 and intersecting groove 908 define a portion of an aspiration flow path configured to drain the volume between the HRVA and the ion-exchange membrane. In FIG. 9, the membrane frame comprises an aspiration port 910, which is in fluid communication with the grooves 906, 908, and a pump (e.g., pump 130). The pump can be used to create a pressure differential and thereby aspirate the

catholyte via the aspiration flow path. In some examples, as discussed above, the aspiration port may further be used to backfill deionized water (or another suitable liquid) into the grooves 906, 908, and the frame cells 904, to flush remaining catholyte from the electrodeposition tool.

**[0088]** One or more of the plurality of the frame cells may include openings that enable fluid communication between the frame cell and the intersecting groove. For instance, in FIG. 9, an opening 912 enables fluid communication between the intersecting groove 908 and a neighboring frame cell of the plurality of frame cells 904. Any or all of the frame cells neighboring the intersecting groove may in some cases include openings to the intersecting groove, to thereby enable flow of catholyte from the frame cells into the intersecting groove.

**[0089]** In some examples, the membrane frame may have a sloping profile. In other words, the perimeter groove 906 may define a plane parallel to the page, as depicted in FIG. 9. As the intersecting groove 908 extends from an opening in the perimeter groove towards the center of the membrane frame, the intersecting groove is not parallel to the plane of the perimeter groove, but rather extends into the page. In this manner, the center of the intersecting groove may be relatively more distal from the plane of the perimeter groove than other points along the intersecting groove. When installed in the electrodeposition tool, this sloping profile may cause liquid to drain toward the center of the intersecting groove, as aided by gravity.

**[0090]** When the membrane frame has a sloping profile, the degree of the slope may vary depending on the implementation. As one non-limiting example, the membrane frame 900 may have a slope inclination of one degree. As one non-limiting example, the membrane frame 1000 of FIG. 10 may have a slope inclination of seven degrees. Membrane frames with different slope inclinations may in some cases be used for different types of electrodeposition processes.

**[0091]** In some cases, openings may be defined between different frame cells of the plurality of frame cells 904, such that a given frame cell may be in fluid communication with one or more of its neighboring frame cells. FIG. 9 includes a zoomed-in view of a group of frame cells, one of which is labeled as first frame cell 914. It will be understood that the specific arrangement of openings between frame cells shown in FIG. 9 is non-limiting. In, general, different frame cells of the plurality of frame cells 904 may have different numbers of openings to their orthogonally and/or diagonally neighboring frame cells. Furthermore, different membrane frames may have

different arrangements of openings connecting their respective frame cells. For instance, an alternate arrangement of frame cell openings will be described below with respect to FIG. 10.

**[0092]** The first frame cell 914 includes an opening 916 to a diagonally adjacent second frame cell 918 of the plurality of frame cells. This may enable catholyte in frame cell 918 to drain through the opening 916 into frame cell 914, toward the intersecting groove. In the case of frame cell 914, it is connected to two different diagonally adjacent frame cells, although this is non-limiting, and other examples can have other configurations. In general, a frame cell of the plurality of frame cells may include openings to any suitable number of its diagonally adjacent neighbors, including no openings to diagonally adjacent neighbors.

**[0093]** In the example of FIG. 9, the first frame cell further includes a second opening 920 to an orthogonally adjacent third frame cell 922 of the plurality of frame cells. This enables flow of catholyte from frame cell 914 through the opening 920 into the frame cell 922, toward the intersecting groove. In general, a frame cell of the plurality of frame cells may include openings to any suitable number of its orthogonally adjacent neighbors, including none of them.

**[0094]** In some examples, in order to further facilitate aspiration of catholyte from the volume between the ion-exchange membrane and the HRVA, one or more of the plurality of frame cells may include openings to the perimeter groove. For instance, in FIG. 9, a frame cell 924 of the plurality of frame cells includes an opening 926 that enables fluid communication between the frame cell 924 and the perimeter groove 906. This can facilitate draining of catholyte from frame cells that are relatively distal from the intersecting groove, such as frame cell 924. This can further enable flushing of catholyte from the membrane frame during backfilling via the aspiration port – e.g., opening 926 may enable deionized water to flow from the perimeter groove into frame cell 924, and other frame cells in fluid communication with frame cell 924.

**[0095]** FIG. 10 shows another example of a membrane frame 1000. The membrane frame 1000 can serve as the membrane frame 128 of FIG. 1. Like the membrane frame 200 of FIGS. 2-4, the membrane frame 1000 comprises a grid structure 1002 comprising a plurality of frame cells 1004 that expose an underlying ion-exchange membrane. The membrane frame additionally includes a groove 1006. In this example, the groove 1006 is a perimeter groove that circumscribes the plurality of frame cells

1004. The membrane further includes an intersecting groove 1008A that extends between openings in the perimeter groove 1006.

[0096] In this example, the intersecting groove 1008A is one of several intersecting grooves that divide the plurality of frame cells into different cell volumes. Specifically, in this example, there are a total of eight intersecting grooves 1008A-1008G, each extending between different respective pairs of openings in the perimeter groove 1006. In this manner, the perimeter groove and the intersecting grooves together define a portion of the aspiration flow path that enables aspiration of the catholyte.

[0097] In this example, the intersecting grooves divide the plurality of cell frames into separate cell volumes 1010A-H. Each intersecting groove includes one or more openings to a different respective cell volume. FIG. 10 includes a zoomed-in view of a frame cell 1012 of the plurality of frame cells 1004. Frame cell 1012 is included in cell volume 1010C, and includes an opening 1014 to intersecting groove 1008C. Frame cell 1012 additionally includes openings to other frame cells in the same cell volume 1010C. For instance, frame cell 1012 includes an opening 1016 to a diagonally adjacent frame cell 1018. This enables catholyte within frame cells of the cell volume 1010C to drain into the intersecting groove 1008C, and eventually be aspirated from the electrodeposition tool via an aspiration port.

[0098] Similarly, intersecting groove 1008B may include one or more openings to frame cells in cell volume 1010B, intersecting groove 1008A may include one or more openings to frame cells in cell volume 1010A, etc. In this manner, catholyte within each cell volume may be aspirated separately through the different intersecting grooves into the perimeter groove. Furthermore, in the example of FIG. 10, different frame cells of the plurality of frame cells lack openings to their orthogonally adjacent neighboring frame cells. As discussed above, the membrane frame 1000 of FIG. 10 may have a sloped profile with a steeper inclination (e.g., a seven degree inclination), as compared to the membrane frame 900 of FIG. 9. This steeper slope may improve draining of catholyte toward the center of the membrane frame, which enables omission of openings between orthogonally adjacent frame cells while still providing for effective catholyte aspiration. To the contrary, it is believed that inclusion of openings between orthogonally neighboring frame cells in a membrane frame with a relatively steeper sloping profile, as is the case in FIG. 10, can “short circuit” and reduce the efficacy of the aspiration process.

[0099] This disclosure is presented by way of example and with reference to the associated drawing figures. Components, process steps, and other elements that can be substantially the same in one or more of the figures are identified coordinately and are described with minimal repetition. It will be noted, however, that elements identified coordinately can also differ to some degree. It will be further noted that some figures can be schematic and not drawn to scale. The various drawing scales, aspect ratios, and numbers of components shown in the figures can be purposely distorted to make certain features or relationships easier to see.

[00100] “And/or” as used herein is defined as the inclusive or  $\vee$ , as specified by the following truth table:

| A     | B     | $A \vee B$ |
|-------|-------|------------|
| True  | True  | True       |
| True  | False | True       |
| False | True  | True       |
| False | False | False      |

[00101] The terminology “one or more of A or B” as used herein comprises A, B, or a combination of A and B. The terminology “one or more of A, B, or C” is equivalent to A, B, and/or C. As such, “one or more of A, B, or C” as used herein comprises A individually, B individually, C individually, a combination of A and B, a combination of A and C, a combination of B and C, or a combination of A, B and C.

[00102] It will be understood that the configurations and/or approaches described herein are example in nature, and that these specific embodiments or examples are not to be considered in a limiting sense, because numerous variations are possible. The specific routines or methods described herein can represent one or more of any number of strategies. As such, various acts illustrated and/or described can be performed in the sequence illustrated and/or described, in other sequences, in parallel, or omitted. Likewise, the order of the above-described processes can be changed.

[00103] The subject matter of the present disclosure includes all novel and non-obvious combinations and sub-combinations of the various processes, systems and configurations, and other features, functions, acts, and/or properties disclosed herein, as well as any and all equivalents thereof.

## CLAIMS

1. An electrodeposition tool, comprising:
  - an anode chamber;
  - a cathode chamber;
  - a high-resistance virtual anode (HRVA) positioned within the cathode chamber;
  - an ion-exchange membrane positioned between the anode chamber and the cathode chamber, the ion-exchange membrane being supported by a membrane frame;
  - and
  - an aspiration flow path configured to drain a volume between the HRVA and the ion-exchange membrane, the aspiration flow path being defined by the ion-exchange membrane and a groove in the membrane frame.
2. The electrodeposition tool of claim 1, wherein the groove is a perimeter groove that is formed at least partially around a perimeter of the membrane frame.
3. The electrodeposition tool of claim 2, wherein the membrane frame includes a plurality of frame cells that are circumscribed by the perimeter groove, and wherein the membrane frame further includes an intersecting groove that extends between opposing openings in the perimeter groove.
4. The electrodeposition tool of claim 3, wherein the membrane frame includes two or more intersecting grooves, wherein the plurality of frame cells is divided into two or more separate cell volumes, and wherein each intersecting groove includes an opening to a different respective cell volume of the two or more separate cell volumes.
5. The electrodeposition tool of claim 3, wherein a first frame cell of the plurality of frame cell includes an opening to a diagonally adjacent second frame cell of the plurality of frame cells.
6. The electrodeposition tool of claim 5, wherein the first frame cell further includes a second opening to an orthogonally adjacent third frame cell of the plurality of frame cells.

7. The electrodeposition tool of claim 3, wherein a frame cell of the plurality of frame cells includes an opening to the perimeter groove.
8. The electrodeposition tool of claim 1, wherein the membrane frame further comprises an aspiration port in fluid communication with the groove, wherein the aspiration port is in fluid communication with a pump.
9. The electrodeposition tool of claim 1, wherein the membrane frame comprises a baffle that extends toward the HRVA, and wherein the groove is formed in the baffle.
10. The electrodeposition tool of claim 9, wherein the baffle comprises a plurality of openings, and wherein two or more of the plurality of openings are located on opposite sides of the baffle.
11. The electrodeposition tool of claim 9, wherein the baffle comprises a plurality of openings, and wherein the two or more openings are offset along a length of the baffle.
12. The electrodeposition tool of claim 9, wherein the baffle is one of a plurality of baffles that divide the volume between the HRVA and the ion-exchange membrane into a plurality of differently sized volumes, wherein a largest volume of the plurality of differently sized volumes is located between a pair of baffles closer to an aspiration port, and wherein a smallest volume of the plurality of differently sized volumes is located between a perimeter of the membrane frame and a baffle farther from the aspiration port.
13. The electrodeposition tool of claim 1, wherein the aspiration flow path further comprises a tube extending from the membrane frame into the volume between the HRVA and the ion-exchange membrane.
14. A membrane frame for an electrodeposition tool, the membrane frame comprising:
  - a plurality of baffles, wherein each baffle of the plurality of baffles extends between opposing locations along a perimeter of the membrane frame; and

a groove formed in one or more of the perimeter of the membrane frame or at least one baffle of the plurality of baffles, the groove configured to define an aspiration flow path to drain a volume between a high-resistance virtual anode (HRVA) and an ion-exchange membrane when the ion-exchange membrane is positioned on the membrane frame and when the membrane frame is positioned in the electrodeposition tool.

15. A method of draining a volume of a catholyte from a volume between a high-resistance virtual anode (HRVA) and an ion-exchange membrane in an electrodeposition tool, the method comprising:

creating a pressure differential to move the volume of the catholyte through an aspiration port in fluid communication with an aspiration flow path defined by the ion-exchange membrane and a groove in a membrane frame.

16. The method of claim 15, wherein creating the pressure differential to move the volume of the catholyte comprises drawing a vacuum through the aspiration port.

17. The method of claim 15, wherein moving the volume of the catholyte comprises moving the volume of the catholyte through a portion of the groove formed in a baffle.

18. The method of claim 17, wherein moving the volume of the catholyte comprises moving at least a portion of the volume of the catholyte through a plurality of openings in the baffle.

19. The method of claim 15, wherein moving the volume of the catholyte comprises draining a plurality of differently sized volumes formed by a plurality of baffles.

20. The method of claim 15, further comprising supplying deionized water to the aspiration port to backfill the deionized water into the volume between the HRVA and the ion-exchange membrane.