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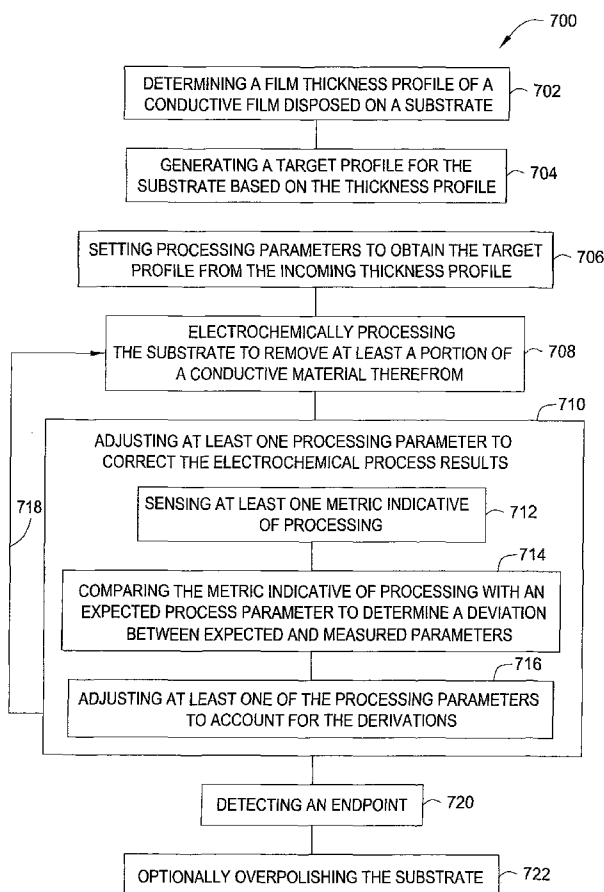
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(54) Title: ELECTROCHEMICAL PROCESSING WITH DYNAMIC PROCESS CONTROL



(57) Abstract: Embodiments of the invention generally provide a method for electrochemically removing material from a substrate. In one embodiment, a method for electrochemically processing a substrate includes determining a process target for a substrate; electrochemically processing the substrate; determining a deviation between expected and actual process indicators while processing, and changing at least one process variable during processing in response to the variation.

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ELECTROCHEMICAL PROCESSING WITH DYNAMIC PROCESS CONTROL

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[0001] Embodiments of the present invention generally relate to a method for processing a substrate, and more specifically, to a method for electrochemically assisted removal of material from a substrate.

DESCRIPTION OF THE RELATED ART

[0002] Planarization techniques are utilized in high-density, multi-layer interconnect fabrication schemes. Chemical mechanical polishing (CMP) is one technique commonly used to planarize a layer of material in interconnect fabrication schemes, such as damascene and dual damascene structures. Recently, electrically-assisted chemical mechanical processing has been developed to remove conductive and other materials from the substrate. Electrochemical mechanical polishing (ECMP) has demonstrated great promise due to the ability to planarize materials utilizing low sheer forces with minimal dishing of filled features. Examples of a tool and a method for ECMP are disclosed in United States Patent Application Serial No. 10/980,888 and United States Patent Application Serial No. 10/941,060.

[0003] One advantage of ECMP is the ability to tailor the process to accounts for variations in the incoming topography of the substrate during the planarization process. For example, using the relationship between charge removed from a conductive surface during polishing, the localized polishing rate may be varied across the substrate surface remove more material in regions of greater film thickness without removing excess material from regions having thinner film thickness. This process is described in United States Patent Application Serial No. 10/456,851.

[0004] Although the aforementioned processes have demonstrated robust processing results, the continuing demand for strict process controls to enable ever diminishing critical dimensions makes all improvements in this area highly desirable. Thus, there is a need for an improved planarization process.

SUMMARY OF THE INVENTION

[0005] Embodiments of the invention generally provide a method for electrochemically removing material from a substrate. In one embodiment, a method for electrochemically processing a substrate includes determining a process target for a substrate, electrochemically processing the substrate, determining a deviation between expected and actual process indicators while processing, and changing at least one process variable during processing in response to the variation.

[0006] In another embodiment, a method for electrochemically processing a substrate includes determining a target profile and expected process indicators for achieving the target profile, contacting a conductive surface of a substrate to a processing pad assembly, the pad assembly comprising an electrode having a plurality of zones, establishing a conductive path between the conductive surface of the substrate and at least one zone of the electrode through an electrolyte, independently controlling an electrical bias applied between the conductive surface of the substrate and each zone of the electrode, determining a change in projected processing time required to arrive at the target profile in at least one zone, and adjusting the electrochemical process to compensate for the determined change.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] So that the manner in which the above recited embodiments of the invention are attained and can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered

limiting of its scope, for the invention may admit to other equally effective embodiments.

[0008] Figure 1 is a plan view of an electrochemical mechanical planarizing system;

[0009] Figure 2 is a sectional view of one embodiment of a first electrochemical mechanical planarizing (ECMP) station of the system of Figure 1;

[0010] Figure 3A is a partial sectional view of the bulk ECMP station through two contact assemblies;

[0011] Figures 3B-C are sectional views of alternative embodiments of contact assemblies;

[0012] Figure 3D-E are sectional views of plugs;

[0013] Figures 4 are side, exploded and sectional views of one embodiment of a contact assembly;

[0014] Figure 5 is one embodiment of a contact element;

[0015] Figure 6 is a perspective view of another embodiment of another ECMP station;

[0016] Figure 7 is a flow diagram of one embodiment of a method for electrochemical processing;

[0017] Figure 8A-B depicts a graph illustrating a comparison between a conventional electrochemical process and an electrochemical process performed in accordance with the present invention; and

[0018] Figure 9 is a plan view of one embodiment of a zoned electrode suitable for use in the electrochemical process of the present invention.

[0019] To facilitate understanding, identical reference numerals have been used, wherever possible, to designate identical elements that are common to the figures. It is contemplated that elements of one embodiment may be advantageously utilized in other embodiments without further recitation.

DETAILED DESCRIPTION

[0020] Embodiments for a system and method for removal of conductive and barrier materials from a substrate are provided. Although the embodiments disclosed below focus primarily on removing material from, *e.g.*, planarizing, a

substrate, it is contemplated that the teachings disclosed herein may be used to electroplate a substrate by reversing the polarity of an electrical bias applied between the substrate and an electrode of the system.

APPARATUS

[0021] Figure 1 is a plan view of one embodiment of a planarization system 100 having an apparatus for electrochemically processing a substrate. The exemplary system 100 generally comprises a factory interface 102, a loading robot 104, and a planarizing module 106. The loading robot 104 is disposed proximate the factory interface 102 and the planarizing module 106 to facilitate the transfer of substrates 122 therebetween.

[0022] A controller 108 is provided to facilitate control and integration of the modules of the system 100. The controller 108 comprises a central processing unit (CPU) 110, a memory 112, and support circuits 114. The controller 108 is coupled to the various components of the system 100 to facilitate control of, for example, the planarizing, cleaning, and transfer processes.

[0023] The factory interface 102 generally includes a metrology module 190, a cleaning module 116 and one or more wafer cassettes 118. An interface robot 120 is employed to transfer substrates 122 between the wafer cassettes 118, the cleaning module 116 and an input module 124. The input module 124 is positioned to facilitate transfer of substrates 122 between the planarizing module 106 and the factory interface 102 by grippers, for example vacuum grippers or mechanical clamps.

[0024] The metrology module 190 is a non-destructive measuring device suitable for providing a metric indicative of the thickness profile of a substrate. The metrology module 190 may include eddy sensors, an interferometer, a capacitance sensor and other suitable devices. Examples of suitable metrology modules include iScanTM and iMapTM substrate metrology modules, available from Applied Materials, Inc. The metrology module 190 provides the metric to the controller 108 wherein a target removal profile is determined for the specific thickness profile measured from the substrate.

[0025] The planarizing module 106 includes at least a first electrochemical mechanical planarizing (ECMP) station 128, disposed in an environmentally

controlled enclosure 188. Examples of planarizing modules 106 that can be adapted to benefit from the invention include MIRRA[®], MIRRA MESA[™], REFLEXION[®], REFLEXION[®] LK, and REFLEXION LK Ecmp[™] Chemical Mechanical Planarizing Systems, all available from Applied Materials, Inc. of Santa Clara, California. Other planarizing modules, including those that use processing pads, planarizing webs, or a combination thereof, and those that move a substrate relative to a planarizing surface in a rotational, linear or other planar motion may also be adapted to benefit from the invention.

[0026] In the embodiment depicted in Figure 1, the planarizing module 106 includes the first ECMP station 128, a second ECMP station 130 and a CMP station 132. Bulk removal of conductive material disposed on the substrate 122 may be performed through an electrochemical dissolution process at the first ECMP station 128. After the bulk material removal at the first ECMP station 128, the remaining conductive material is removed from the substrate at the second ECMP station 130 through a multi-step electrochemical mechanical process, wherein part of the multi-step process is configured to remove residual conductive material. It is contemplated that more than one ECMP station may be utilized to perform the multi-step removal process after the bulk removal process performed at a different station. Alternatively, each of the first and second ECMP stations 128, 130 may be utilized to perform both the bulk and multi-step conductive material removal on a single station. It is also contemplated that the stations 128, 130, 132 may be configured to electrochemically process the conductive layer.

[0027] The exemplary planarizing module 106 also includes a transfer station 136 and a carousel 134 that are disposed on an upper or first side 138 of a machine base 140. In one embodiment, the transfer station 136 includes an input buffer station 142, an output buffer station 144, a transfer robot 146, and a load cup assembly 148. The input buffer station 142 receives substrates from the factory interface 102 by means of the loading robot 104. The loading robot 104 is also utilized to return polished substrates from the output buffer station 144 to the factory interface 102. The transfer robot 146 is utilized to move substrates between the buffer stations 142, 144 and the load cup assembly 148.

[0028] In one embodiment, the transfer robot 146 includes two gripper assemblies, each having pneumatic gripper fingers that hold the substrate by the substrate's edge. The transfer robot 146 may simultaneously transfer a substrate to be processed from the input buffer station 142 to the load cup assembly 148 while transferring a processed substrate from the load cup assembly 148 to the output buffer station 144. An example of a transfer station that may be used to advantage is described in United States Patent No. 6,156,124, issued December 5, 2000 to Tobin.

[0029] The carousel 134 is centrally disposed on the base 140. The carousel 134 typically includes a plurality of arms 150, each supporting a carrier head assembly 152. Two of the arms 150 depicted in Figure 1 are shown in phantom such that the transfer station 136 and a planarizing surface 126 of the first ECMP station 128 may be seen. The carousel 134 is indexable such that the carrier head assemblies 152 may be moved between the planarizing stations 128, 130, 132 and the transfer station 136. One carousel that may be utilized to advantage is described in United States Patent No. 5,804,507, issued September 8, 1998 to Perlov, et al.

[0030] A conditioning device 182 is disposed on the base 140 adjacent each of the planarizing stations 128, 130, 132. The conditioning device 182 periodically conditions the planarizing material disposed in the stations 128, 130, 132 to maintain uniform planarizing results.

[0031] Figure 2 depicts a sectional view of one of the carrier head assemblies 152 positioned over one embodiment of the first ECMP station 128. The second and third ECMP stations 130, 132 may be similarly configured. The carrier head assembly 152 generally comprises a drive system 202 coupled to a carrier head 204. The drive system 202 generally provides at least rotational motion to the carrier head 204. The carrier head 204 additionally may be actuated toward the first ECMP station 128 such that the substrate 122 retained in the carrier head 204 may be disposed against the planarizing surface 126 of the first ECMP station 128 during processing. The drive system 202 is coupled to the controller 108 that provides a signal to the drive system 202 for controlling the rotational speed and direction of the carrier head 204.

[0032] In one embodiment, the carrier head may be a TITAN HEAD™ or TITAN PROFILER™ wafer carrier manufactured by Applied Materials, Inc. Generally, the carrier head 204 comprises a housing 214 and retaining ring 224 that defines a center recess in which the substrate 122 is retained. The retaining ring 224 circumscribes the substrate 122 disposed within the carrier head 204 to prevent the substrate from slipping out from under the carrier head 204 while processing. The retaining ring 224 can be made of plastic materials such as PPS, PEEK, and the like, or conductive materials such as stainless steel, Cu, Au, Pd, and the like, or some combination thereof. It is further contemplated that a conductive retaining ring 224 may be electrically biased to control the electric field during ECMP. Conductive or biased retaining rings tend to slow the polishing rate proximate the edge of the substrate. It is contemplated that other carrier heads may be utilized.

[0033] The first ECMP station 128 generally includes a platen assembly 230 that is rotationally disposed on the base 140. The platen assembly 230 is supported above the base 140 by a bearing 238 so that the platen assembly 230 may be rotated relative to the base 140. An area of the base 140 circumscribed by the bearing 238 is open and provides a conduit for the electrical, mechanical, pneumatic, control signals and connections communicating with the platen assembly 230.

[0034] Conventional bearings, rotary unions and slip rings, collectively referred to as rotary coupler 276, are provided such that electrical, mechanical, fluid, pneumatic, control signals and connections may be coupled between the base 140 and the rotating platen assembly 230. The platen assembly 230 is typically coupled to a motor 232 that provides the rotational motion to the platen assembly 230. The motor 232 is coupled to the controller 108 that provides a signal for controlling for the rotational speed and direction of the platen assembly 230.

[0035] A top surface 260 of the platen assembly 230 supports a processing pad assembly 222 thereon. The processing pad assembly 222 may be retained to the platen assembly 230 by magnetic attraction, vacuum, clamps, adhesives and the like.

[0036] A plenum 206 is defined in the platen assembly 230 to facilitate uniform distribution of electrolyte to the planarizing surface 126. A plurality of passages are formed in the platen assembly 230 to allow electrolyte, provided to the plenum 206 from an electrolyte source 248, to flow uniformly through the platen assembly 230 and into contact with the substrate 122 during processing. It is contemplated that different electrolyte compositions may be provided during different stages of processing or at different stations 128, 130, 132. It is also contemplated that electrolyte may be provided to the surface of the pad assembly 222 via a nozzle supported over the pad assembly by a fluid delivery arm.

[0037] The processing pad assembly 222 includes an electrode 292 and at least a planarizing portion 290. The electrode 292 is typically comprised of a conductive material, such as stainless steel, copper, aluminum, gold, silver and tungsten, among others. The electrode 292 may be solid, impermeable to electrolyte, permeable to electrolyte or perforated. The electrode 292 may comprise one or more zones coupled to the power source 242. In embodiments wherein the electrode 292 includes a plurality of zones, each zone may be biased by the power source 242 independently from a bias applied to the other zones.

[0038] Figure 9 is a plan view of one embodiment of an electrode 292 having a plurality of zones, with five concentric zones 902, 904, 906, 908, 910 being shown individually coupled to the power source 242. It is contemplated that zones of the electrode 292 may have other geometric configurations, number and distributions in the pad assembly 222.

[0039] Continuing to refer to Figure 2, at least one contact assembly 250 extends above the processing pad assembly 222 and is coupled to the power source 242. During processing, the contact assembly 250 electrically couples the substrate being processed on the processing pad assembly 222 to the power source 242 so that an electrical potential is established between the substrate and electrode 292.

[0040] A sensor or meter 244 is provided to detect a metric indicative of the electrochemical process. The meter 244 may be coupled or positioned between the power source 242 and at least one of the electrode 292 or contact

assembly 250. The meter 244 may also be integral to the power source 242. In one embodiment, the meter 244 is configured to provide the controller 108 with a metric indicative of processing, such a charge, current and/or voltage, occurring over each zone of the electrode 292 (as shown in Figure 9). This metric may be utilized by the controller 108 to adjust the processing parameters *in-situ* or to facilitate endpoint or other process stage detection. In one embodiment, the controller 108 utilizes the metric provided by the meter 244 to control the rate and/or profile of the rate of material removal *in-situ* processing (*i.e.*, adjust the processing parameters for a substrate from which with metric of processing performance was obtained).

[0041] A window 246 is provided through the pad assembly 222 and/or platen assembly 230, and is configured to allow a sensor 254, positioned below the pad assembly 222, to sense a metric indicative of polishing performance. For example, the sensor 254 may be an eddy current sensor or an interferometer, among other sensors. The metric, provided by the sensor 254 to the controller 108, provides information that may be utilized for processing profile adjustment *in-situ*, endpoint detection or detection of another point in the electrochemical process. In one embodiment, the sensor 254 an interferometer capable of generating a collimated light beam, which during processing, is directed at and impinges on a side of the substrate 122 that is being polished. The interference between reflected signals is indicative of the thickness of the conductive layer of material being processed. One sensor that may be utilized to advantage is described in United States Patent No. 5,893,796, issued April 13, 1999, to Birang, et al.

[0042] Embodiments of the processing pad assembly 222 suitable for removal of conductive material from the substrate 122 may generally include a planarizing surface 126 that is substantially dielectric. Other embodiments of the processing pad assembly 222 suitable for removal of conductive material from the substrate 122 may generally include a planarizing surface 126 that is substantially conductive. At least one contact assembly 250 is provided to couple the substrate to the power source 242 so that the substrate may be biased relative to the electrode 292 during processing. Apertures 210, formed

through the planarizing layer 290, allow the electrolyte to establish a conductive path between the substrate 122 and electrode 292.

[0043] In one embodiment, the planarizing portion 290 of the processing pad assembly 222 is a dielectric, such as polyurethane. Examples of processing pad assemblies that may be adapted to benefit from the invention are described in United States Patent Application Serial No. 10/455,941, filed June 6, 2003 by Y. Hu et al. (entitled "CONDUCTIVE PLANARIZING ARTICLE FOR ELECTROCHEMICAL MECHANICAL PLANARIZING") and United States Patent Application Serial No. 10/455,895, filed June 6, 2003 by Y. Hu et al. (entitled "CONDUCTIVE PLANARIZING ARTICLE FOR ELECTROCHEMICAL MECHANICAL PLANARIZING").

[0044] Figure 3A is a partial sectional view of the first ECMP station 128 through two contact assemblies 250, and Figures 4A-C are side, exploded and sectional views of one of the contact assemblies 250 shown in Figures 3A. The platen assembly 230 includes at least one contact assembly 250 projecting therefrom and coupled to the power source 242 that is adapted to bias a surface of the substrate 122 during processing. The contact assemblies 250 may be coupled to the platen assembly 230, part of the processing pad assembly 222, or a separate element. Although two contact assemblies 250 are shown in Figure 3A, any number of contact assemblies may be utilized and may be distributed in any number of configurations relative to the centerline of the platen assembly 230.

[0045] The contact assemblies 250 are generally electrically coupled to the power source 242 through the platen assembly 230 and are movable to extend at least partially through respective apertures 368 formed in the processing pad assembly 222. The positions of the contact assemblies 250 may be chosen to have a predetermined configuration across the platen assembly 230. For predefined processes, individual contact assemblies 250 may be repositioned in different apertures 368, while apertures not containing contact assemblies may be plugged with a stopper 392 or filled with a nozzle 394 (as shown in Figures 3D-E) that allows flow of electrolyte from the plenum 206 to the substrate. One contact assembly that may be adapted to benefit from the invention is described

in United States Patent Application Serial No. 10/445,239, filed May 23, 2003, by Butterfield, *et al.*

[0046] Although the embodiments of the contact assembly 250 described below with respect to Figure 3A depicts a rolling ball contact, the contact assembly 250 may alternatively comprise a structure or assembly having a conductive upper layer or surface suitable for electrically biasing the substrate 122 during processing. For example, as depicted in Figure 3B, the contact assembly 250 may include a pad structure 350 having an upper layer 352 made from a conductive material or a conductive composite (*i.e.*, the conductive elements are dispersed integrally with or comprise the material comprising the upper surface), such as a polymer matrix 354 having conductive particles 356 dispersed therein or a conductive coated fabric, among others. The pad structure 350 may include one or more of the apertures 210 formed therethrough for electrolyte delivery to the upper surface of the pad assembly. Other examples of suitable contact assemblies are described in United States Patent Application Serial No. 10/980,888, filed November 3, 1994, by Hu, *et al.*

[0047] In one embodiment, each of the contact assemblies 250 includes a hollow housing 302, an adapter 304, a ball 306, a contact element 314 and a clamp bushing 316. The ball 306 has a conductive outer surface and is movably disposed in the housing 302. The ball 306 may be disposed in a first position having at least a portion of the ball 306 extending above the planarizing surface 126 and at least a second position where the ball 306 is substantially flush with the planarizing surface 126. It is also contemplated that the ball 306 may move completely below the planarizing surface 126. The ball 306 is generally suitable for electrically coupling the substrate 122 to the power source 242. It is contemplated that a plurality of balls 306 for biasing the substrate may be disposed in a single housing 358 as depicted in Figure 3C.

[0048] The power source 242 generally provides a positive electrical bias to the ball 306 during processing. Between planarizing substrates, the power source 242 may optionally apply a negative bias to the ball 306 to minimize attack on the ball 306 by process chemistries.

[0049] The housing 302 is configured to provide a conduit for the flow of electrolyte from the source 248 to the substrate 122 during processing. The

housing 302 is fabricated from a dielectric material compatible with process chemistries. A seat 326 formed in the housing 302 prevents the ball 306 from passing out of the first end 308 of the housing 302. The seat 326 optionally may include one or more grooves 348 formed therein that allow fluid flow to exit the housing 302 between the ball 306 and seat 326. Maintaining fluid flow past the ball 306 may minimize the propensity of process chemistries to attack the ball 306.

[0050] The contact element 314 is coupled between the clamp bushing 316 and the adapter 304. The contact element 314 is generally configured to electrically connect the adapter 304 and ball 306 substantially or completely through the range of ball positions within the housing 302. In one embodiment, the contact element 314 may be configured as a spring form.

[0051] In the embodiment depicted in Figures 3 and 4A-C and detailed in Figure 5, the contact element 314 includes an annular base 342 having a plurality of flexures 344 extending therefrom in a polar array. The flexure 344 is generally fabricated from a resilient and conductive material suitable for use with process chemistries. In one embodiment, the flexure 344 is fabricated from gold plated beryllium copper.

[0052] Returning to Figures 3A and 4A-B, the clamp bushing 316 includes a flared head 424 having a threaded post 422 extending therefrom. The clamp bushing 316 may be fabricated from either a dielectric or conductive material, or a combination thereof, and in one embodiment, is fabricated from the same material as the housing 302. The flared head 424 maintains the flexures 344 at an acute angle relative to the centerline of the contact assembly 250 so that the flexures 344 of the contact elements 314 are positioned to spread around the surface of the ball 306 to prevent bending, binding and/or damage to the flexures 344 during assembly of the contact assembly 250 and through the range of motion of the ball 306.

[0053] The ball 306 may be solid or hollow and is typically fabricated from a conductive material. For example, the ball 306 may be fabricated from a metal, conductive polymer or a polymeric material filled with conductive material, such as metals, conductive carbon or graphite, among other conductive materials. Alternatively, the ball 306 may be formed from a solid or

hollow core that is coated with a conductive material. The core may be non-conductive and at least partially coated with a conductive covering.

[0054] The ball 306 is generally actuated toward the planarizing surface 126 by at least one of spring, buoyant or flow forces. In the embodiment depicted in Figure 3, flow through the passages formed through the adapter 304 and clamp bushing 316 and the platen assembly 230 from the electrolyte source 248 urge the ball 306 into contact with the substrate during processing.

[0055] Figure 6 is a sectional view of one embodiment of the second ECMP station 130. Optionally, the first and third stations 128, 132 may be configured similarly. The second ECMP station 130 generally includes a platen 602 that supports a fully conductive processing pad assembly 604. The platen 602 may be configured similar to the platen assembly 230 described above to deliver electrolyte through the processing pad assembly 604, or the platen 602 may have a fluid delivery arm 606 disposed adjacent thereto configured to supply electrolyte to a planarizing surface of the processing pad assembly 604. The second ECMP station 130 also includes at least one of a meter 244 or sensor 254 (shown in Figure 2) for obtaining at least one metric indicative of processing to facilitate endpoint detection and/or process control.

[0056] In one embodiment, the processing pad assembly 604 includes interposed pad 612 sandwiched between a conductive pad 610 and an electrode 614. The electrode 614 is generally configured as described with reference to the electrode 292. The conductive pad 610 is substantially conductive across its top processing surface and is generally made from a conductive material or a conductive composite (*i.e.*, the conductive elements are dispersed integrally with or comprise the material comprising the planarizing surface), such as a polymer matrix having conductive particles dispersed therein or a conductive coated fabric, among others. The conductive pad 610, the interposed pad 612, and the electrode 614 may be fabricated into a single, replaceable assembly. The processing pad assembly 604 is generally permeable or perforated to allow electrolyte to pass between the electrode 614 and top surface 620 of the conductive pad 610. In the embodiment depicted in Figure 6, the processing pad assembly 604 is perforated by apertures 622 to allow electrolyte to flow therethrough. In one embodiment, the conductive pad

610 is comprised of a conductive material disposed on a polymer matrix disposed on a conductive fiber, for example, tin particles in a polymer matrix disposed on a woven copper coated polymer. The conductive pad 610 may also be utilized for the contact assembly 250 in the embodiment of Figure 3C.

[0057] A conductive foil 616 may additionally be disposed between the conductive pad 610 and the subpad 612. The foil 616 is coupled to a power source 242 and provides uniform distribution of voltage applied by the source 242 across the conductive pad 610. In embodiments not including the conductive foil 616, the conductive pad 610 may be coupled directly, for example, via a terminal integral to the pad 610, to the power source 242. Additionally, the pad assembly 604 may include an interposed pad 618, which, along with the foil 616, provides mechanical strength to the overlying conductive pad 610. Examples of suitable pad assemblies are described in the previously mentioned U.S. Patent Applications 10/455,941 and 10/455,895.

METHOD FOR ELECTROPROCESSING METAL AND BARRIER LAYERS

[0058] Figure 7 depicts a flow diagram of one embodiment of a method 700 for electroprocessing a substrate having an exposed conductive layer that may be practiced on the system 100 described above, or other suitable processing system. The method 700 is generally stored in the memory 112 of the controller 108, typically as a software routine. The software routine may also be stored and/or executed by a second CPU (not shown) that is remotely located from the hardware being controlled by the CPU 110. Although the process of the present invention is discussed as being implemented as a software routine, some of the method steps that are disclosed therein may be performed in hardware as well as by the software controller. As such, the invention may be implemented in software as executed upon a computer system, in hardware as an application specific integrated circuit or other type of hardware implementation, or a combination of software and hardware.

[0059] The method 700 begins at step 702 by determining a film thickness profile of a conductive film disposed on a substrate to be processed. The thickness profile may be determined by the metrology module 190 disposed in the factory interface 102, or provided from another source. The thickness

profile is derived from measurements associated with a unique substrate that allow a map of the film thickness and/or topography to be generated, and should not be confused with averaged or spot thickness obtained after, or as an endpoint indicator in, a deposition process. Thus, substrates within a batch will respectively have individual thickness profiles.

[0060] At step 704, a target profile is generated for each substrate based on the information obtained at step 702. The target profile is generally the amount of material that is to be removed at various locations across the substrate so that a planar surface is obtained. For example, the target profile may indicate that a predetermined region defined on the substrate has a thick film layer (relative to other regions of the film, as determined by the incoming profile information), accordingly must have more material removed than another region of the substrate in order to obtain a planar surface. By processing to achieve the target profile, thinner film regions may be processed at a rate that prevents overpolishing or dishing, *e.g.*, unwanted material removal from within a feature, such as a trench.

[0061] At step 706, the starting processing parameters, such as voltage, current, time and the like, of the system 100 are set to obtain the target profile from the incoming profile. This generally sets the duration and voltage (and/or current) needed to removed a predetermined amount of charge (which is indicative of the film thickness) from the substrate. One embodiment for setting parameters to respectfully remove calculated amounts of charge from a substrate in different zones by an electrochemical process is described in the previously mentioned United States Patent Application Serial No. 10/456,851. It is contemplated that the process parameters may be set thought other methods.

[0062] At step 708, the substrate is electrochemically processed to remove at least a portion of a conductive material film (*e.g.*, layer) therefrom. The conductive film may be tungsten, copper, a layer having both exposed tungsten and copper, or other conductive material.

[0063] In one embodiment, the electrochemical processing step 708 includes moving the substrate 122 retained in the carrier head 204 over the processing pad assembly 222 disposed in the first ECMP station 128. Although

the pad assembly of Figures 2, 3A, 4A-C and 5 is utilized in one embodiment, it is contemplated that pad and contact assemblies as described in Figures 3B-C may alternatively be utilized. It is also contemplated that the electrochemical processing step 708 may be performed in the second ECMP station 130 in a manner similar to what is described below.

[0064] The carrier head 204 is lowered toward the platen assembly 222 to place the substrate 122 in contact with the top surface of the pad assembly 222. The substrate 122 is urged against the pad assembly 222 with a force of less than about 2 pounds per square inch (psi). In one embodiment, the force is about 0.3 psi.

[0065] Relative motion is provided between the substrate 122 and processing pad assembly 222. In one embodiment, the carrier head 204 is rotated at about 30-60 revolutions per minute, while the pad assembly 222 is rotated at about 7-35 revolutions per minute.

[0066] Electrolyte is supplied to the processing pad assembly 222 to establish a conductive path therethrough between the substrate 122 and the electrode 292. The electrolyte typically includes at least one of sulfuric acid, phosphoric acid and ammonium citrate.

[0067] The power source 242 provides a bias voltage between the substrate in contact with the top surface of the pad assembly 222 and the electrode 292. In one embodiment, the voltage provided is less than about 6.0 volts. In an embodiment where copper is the material being processed, the voltage is applied at less than about 3.0 volts. In an embodiment where tungsten is the material being processed, the voltage is applied at less than about 3.5 volts.

[0068] The one or more of the contact elements 250 of the pad assembly 222 are in contact with the substrate 122 and allows the voltage to be coupled thereto. Electrolyte filling the apertures 210 between the electrode 292 and the substrate 122 provides a conductive path between the power source 242 and substrate 122 to drive an electrochemical mechanical planarizing process that results in the removal of the conductive material disposed on the substrate, by an anodic dissolution method at step 708. The process of step 708 generally

has a copper removal rate of about 6000 Å/min, while a tungsten removal rate of about 4000 Å/min has been obtained.

[0069] The bias to each zone of the electrode 292 is individually controlled, initially biased on parameters set in step 706. The bias may be controlled by adjusting the voltage applied between the substrate and electrode 292. This allows for the process to be tailored to the specific topography and/or film thickness of the substrate being processed. As the resistance of the film being removed generally rises as the film become thinner, the current passing through the zone (and consequently, the rate of material removal in the region of the substrate being processed over that zone) is reduced.

[0070] At step 710, at least one processing parameter is adjusted to correct the change in processing rate in each zone, for example, as indicated by the change in current passing through the respective zones. The adjustment made in step 710 allows the processing rate to be maintained in each zone at or near the target levels by compensating for the increase resistances or other factors that cause rate change, thereby substantially preventing a reduction in current from the amount desired to obtain the target profile.

[0071] In one embodiment, the adjustment step 710 has three substeps 712, 714, 716. At substep 712, at least one metric indicative of processing, such a charge, current and/or voltage, is provided by the meter 244 (or meters 244) to the controller 108. In one embodiment, the meter 244 provides the amount of charge removed from the substrate in each zone.

[0072] At substep 714, the metric indicative of processing in each zone is compared with the process parameter set at step 706 (or value set at the last iteration) to determine an error. The substrate 714 compares the actual process indicator measured and/or sensed at step 712 with the desired indicator, *e.g.*, the value of the indicator expected when processing at the parameters set at step 706 (or set at the last iteration of step 710). For example, step 706 may have determined that the desired charge at a first zone of the electrode 292 should be (X) in order to achieve the target profile, while the metric sensed during processing at step 712 is (Y). Thus, in this example, the error between the desired and measured metric is (X-Y). It is contemplated that one or more metrics may be compared.

[0073] In substep 716, the process parameters driving the process at step 708 are adjusted to account for derivations between the expected and measured parameter, thus maintaining the process on track to achieve the target profile. In the above, example at least one process parameter would be adjusted to

[0074] In one embodiment, the voltage applied between the substrate and each zone of the electrode 292 may be adjusted to compensate for changes during processing and to maintain the process on track to yield the desired target profile. In the present example, the adjusted voltage (*e.g.*, the voltage corrected at step 712) may be expressed as:

$$V_i(t+\Delta t) = V_i(t) + P \times Ie_i(t) + I \times Ce_i(t) + D \times \frac{d(Ie_i(t))}{dt}$$

where,

$V_i(t+\Delta t)$ is the adjusted voltage for zone_i of the electrode 292;

$V_i(t)$ is the voltage at the time of the last sample (*i.e.*, first at step 706, followed iteratively at substep 712);

i is the zone of the electrode 292;

Ie_i is error in current for zone_i;

Ce_i is error in charge for zone_i; and

P, I, D are proportional, integral and differential constants selected for the process cell of the tool - these may be determine empirically or through computation.

[0075] Factors that may be considered during the determination of the P, I, D constants include the initial voltage, the saturation voltage, the thickness of the incoming film to be processed and the desired removal rate. It has been observed that a large saturation voltage, defined as the maximum voltage change allowed in each adjustment iteration, contributes to process instability. In one embodiment, the saturation voltage is set at less then about 0.5 volts, for example, less than about 0.2 volts, prevents process instability during the iterative process adjustments. The constant D may be set at zero for low current processes, and at higher values for high current processes. The constant D was set to about zero while the constant P was set at about 0.02 for

process utilized to attain the results depicted in Figure 8B, which is discussed further below.

[0076] The steps 708 and 710 are repeated as illustrated by arrow 718 until an endpoint is reached at step 720. The endpoint may be determined using a metric of processing provided by the meter 244. In another embodiment, optical techniques, such as an interferometer utilizing the sensor 254, may be utilized. Alternatively, the remaining thickness may be directly measured or calculated by subtracting the amount of material removed from a predetermined starting film thickness, for example, by comparing the charge removed from the substrate to the target charge correlating to the target profile. Examples of endpoint techniques that may be utilized are described in U.S. Patent Application Serial No. 10/949,160, filed September 24, 2004, U.S. Patent Application Serial No. 10/056,316, filed January 22, 2002, and U.S. Patent Application Serial No. 10/456,851, filed June 6, 2002.

[0077] After the endpoint is reached at 720, and optional overpolish may be performed at step 722. The overpolish step 722 typically has a duration of about 15 to about 30 seconds to clear residue material from the surface of the substrate.

[0078] In another embodiment, the adjustment process 710 may compare the projected time to reach the target criteria in each zone. If the difference between the projected times in the fastest and slowest zones is greater than a predetermined period, then the process in one or more zones may be adjusted so the process is completed (*e.g.*, the targets in each zone are reached) within a predetermined period. By completing processing in all zones close together, inadvertent material removal from the substrate over the zones where the target has been reached earlier is substantially prevented. Moreover, as the process is periodically corrected, any changes in the time to complete the process in any zone may be accounted for across all zones, thereby contributing to minimizing the process time.

[0079] Figures 8A-B depicts graphs 800, 820 respectively illustrating a conventional electroprocess (Figure 8A) and an electroprocess (Figure 8B) of the present invention. The conventional process of Figure 8A is plotted with time on the X-axis 802. Current and charge are plotted on the Y-axis 804.

Plots 806, 808, 810 illustrate the measure of charge over time in a respective first, second and third process zones. Plots 812, 814, 816 illustrate the measure of current respectively in the first, second and third zones over time. The vertical portion of each charge trace 806, 808, 810 indicates the arrival at the target. As shown by arrow 818, arrival at the endpoint of the first zone (represented by trace 806) is greatly offset from the arrival at the endpoint of the third zone (represented by trace 810). The mismatch between endpoints may result in undesired polishing in the completed zones.

[0080] The process of the present invention is illustrated in Figure 8B with time on the X-axis 802 and current and charge on the Y-axis 804. Plots 826, 828, 830 illustrate the measure of charge over time in a respective first, second and third process zones. Plots 832, 834, 836 illustrate the measure of current respectively in the first, second and third zones over time. The vertical portion of each charge trace 826, 828, 830 indicates the arrival at the target. Since the arrival at the endpoint of the first zone (represented by trace 826) may be coordinated with the arrival at the endpoint of the third zone (represented by trace 810) by adjusting the process in response to the comparison between measured and expected process indicators, any offset in the endpoints between the fastest and slowest processing zones may be minimized, as shown by arrow 838. The offset between endpoints may further be minimized by adjusting the process to compensate for changes the projected processing times in each zone.

[0081] Thus, the present invention provides an improved apparatus and method for electrochemically planarizing a substrate. The apparatus advantageously facilitates efficient bulk and residual metal and barrier materials removal from a substrate using a single tool. Utilization of electrochemical processes for full sequence metal and barrier removal advantageously provides low erosion and dishing of conductors while minimizing oxide loss during processing. It is contemplated that a method and apparatus as described by the teachings herein may be utilized to deposit materials onto a substrate by reversing the polarity of the bias applied to the electrode and the substrate.

[0082] While the foregoing is directed to embodiments of the invention, other and further embodiments of the invention may be devised without

departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method for processing a substrate comprising:
determining a process target for a substrate;
electrochemically processing a surface of the substrate;
determining a deviation between expected and actual process indicators while processing; and
changing at least one process variable during processing in response to the variation.
2. The method of claim 1, wherein determining the process target further comprises:
determining a profile for the surface to be processed.
3. The method of claim 1, wherein determining the process target further comprises:
determining the thickness of a film disposed on the substrate in a plurality of locations.
4. The method of claim 3, wherein the thickness is determined through a non-destructive measuring technique.
5. The method of claim 4, wherein the non-destructive measuring technique is at least one of eddy current, capacitance sensing or interferometry.
6. The method of claim 1, wherein changing at least one process variable further comprises:
adjusting a current driving the electrochemical process.
7. The method of claim 1, wherein electrochemically processing the surface further comprises:
pressing the surface of the substrate against a polishing material; and

establishing relative motion between the polishing material and the surface of the substrate.

8. The method of claim 1, wherein electrochemically processing the surface of the substrate further comprises:

basing the surface of the substrate relative to an electrode spaced apart from the surface of the substrate; and

providing an electrolyte in contact with the electrode and the surface of the substrate.

9. The method of claim 1, wherein electrochemically processing the surface of the substrate further comprises:

pressing the surface of the substrate against a conductive polymer surface in the presence of an electrolyte;

applying an electrical bias to the surface of the substrate through the conductive polymer surface; and

providing relative motion between the surface of the substrate and the conductive polymer surface.

10. The method of claim 1, wherein electrochemically processing the surface of the substrate further comprises:

pressing the surface of the substrate against a dielectric polymer surface supported by a platen;

establishing a conductive path between the surface of the substrate and an electrode supported by the platen through an electrolyte;

applying an electrical bias to the surface of the substrate through an electrical contact extending from the platen; and

providing relative motion between the surface of the substrate and the dielectric polymer surface.

11. The method of claim 1, wherein the step of determining further comprises:

comparing an expected current with a measured current.

12. The method of claim 1, wherein the step of determining further comprises:

comparing an expected charge with a measured charge removed from the substrate.

13. The method of claim 1, wherein the step of determining further comprises:

comparing an expected thickness with the actual thickness during the electrochemical process.

14. The method of claim 1, wherein changing at least one process variable further comprises:

adjusting a voltage driving the electrochemical process.

15. The method of claim 1, wherein the step of changing at least one process variable further comprises:

adjusting a process variable in a first process zone independently from a process variable for a second process zone so that an electrochemical removal rate is independently controlled in each process zone.

16. The method of claim 1, wherein a voltage V_i driving the electrochemical process is changed in response to a deviation D_i , wherein V_i is a bias voltage applied in a respective process zone of a processing system wherein the electrochemical process is performed, D_i is a deviation between expected and actual process indicators in a respective process zone of the processing system, and i is the number of laterally arranged process zones in the processing system.

17. The method of claim 16, wherein V_i may be expressed as

$$V_i(t + \Delta t) = V_i(t) + P \times Ie_i(t) + I \times Ce_i(t) D \times \frac{d(Ie_i(t))}{dt}$$

where,

Ie_i is an error in current for zone i ;

Ce_i is error in charge for zone i ; and

P , I and D are constants.

18. The method of claim 1 further comprising:

determining a change in a projected processing time during processing;

and

adjusting the electrochemical process to compensate for the determined change.

19. The method of claim 18, wherein adjusting the electrochemical process to compensate for the determined change further comprises:

maintaining an offset in arrival at an endpoint between a fastest and slowest processing zone within a predetermined period.

20. The method of claim 1 further comprising:

setting process parameters based an incoming thickness profile of a film to be processed on the substrate to yield the process target.

21. A method for processing a substrate comprising:

determining a target profile and expected process indicators for achieving the target profile;

contacting a conductive surface of a substrate to a processing pad assembly, the pad assembly comprising an electrode having a plurality of zones;

establishing a conductive path between the conductive surface of the substrate and at least one zone of the electrode through an electrolyte;

independently controlling an electrical bias applied between the conductive surface of the substrate and each zone of the electrode;

determining a deviation between expected and actual process indicators while processing; and

changing at least one process variable during processing in response to the variation.

22. The method of claim 21 further comprising:

determining a change in a projected processing time during processing; and

adjusting the electrochemical process to compensate for the determined change.

23. The method of claim 22, wherein adjusting the electrochemical process to compensate for the determined change further comprises:

maintaining an offset in arrival at an endpoint between a fastest and slowest processing zone within a predetermined period.

24. A method for processing a substrate comprising:

determining a target profile and expected process indicators for achieving the target profile;

contacting a conductive surface of a substrate to a processing pad assembly, the pad assembly comprising an electrode having a plurality of zones;

establishing a conductive path between the conductive surface of the substrate and at least one zone of the electrode through an electrolyte;

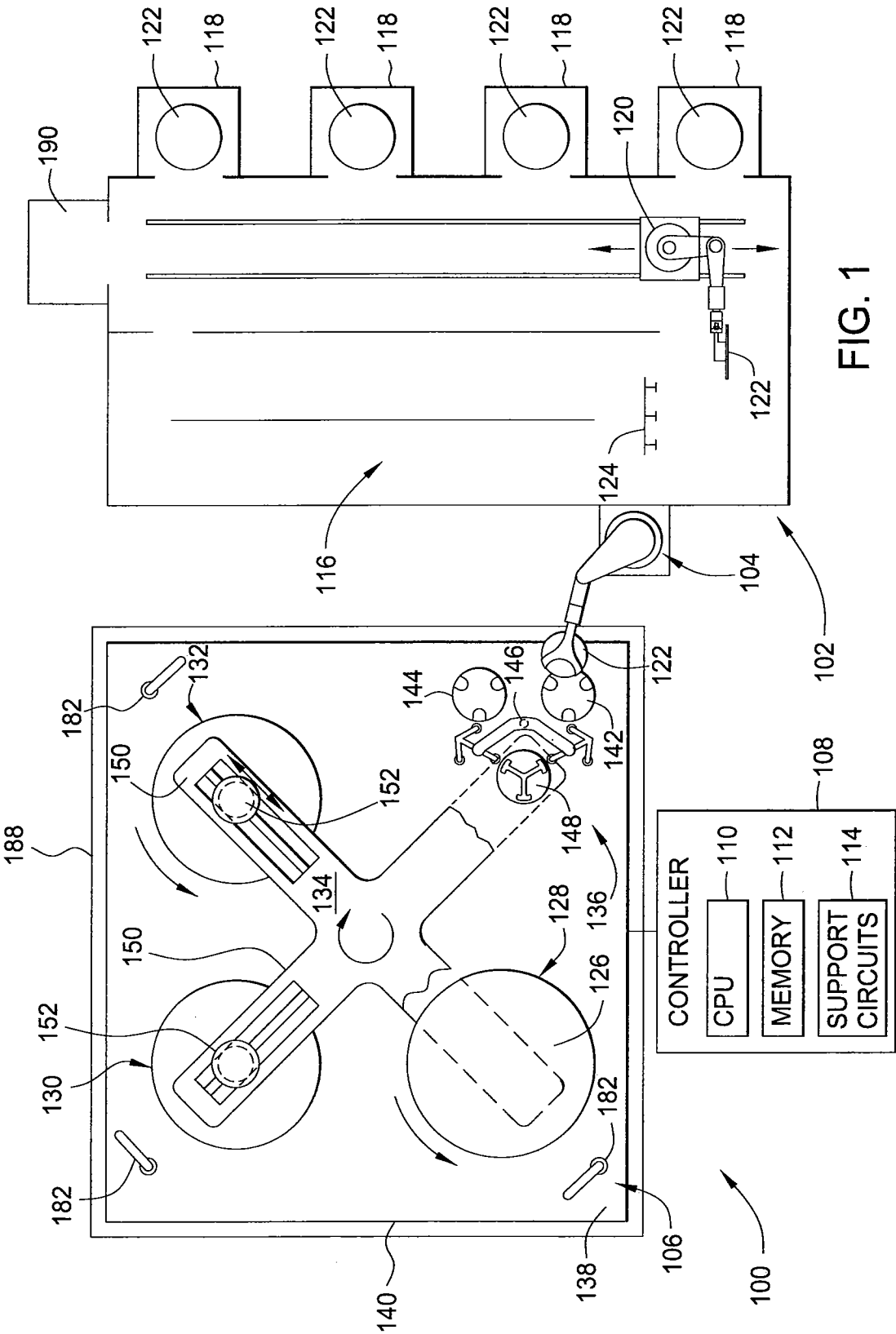
independently controlling an electrical bias applied between the conductive surface of the substrate and each zone of the electrode;

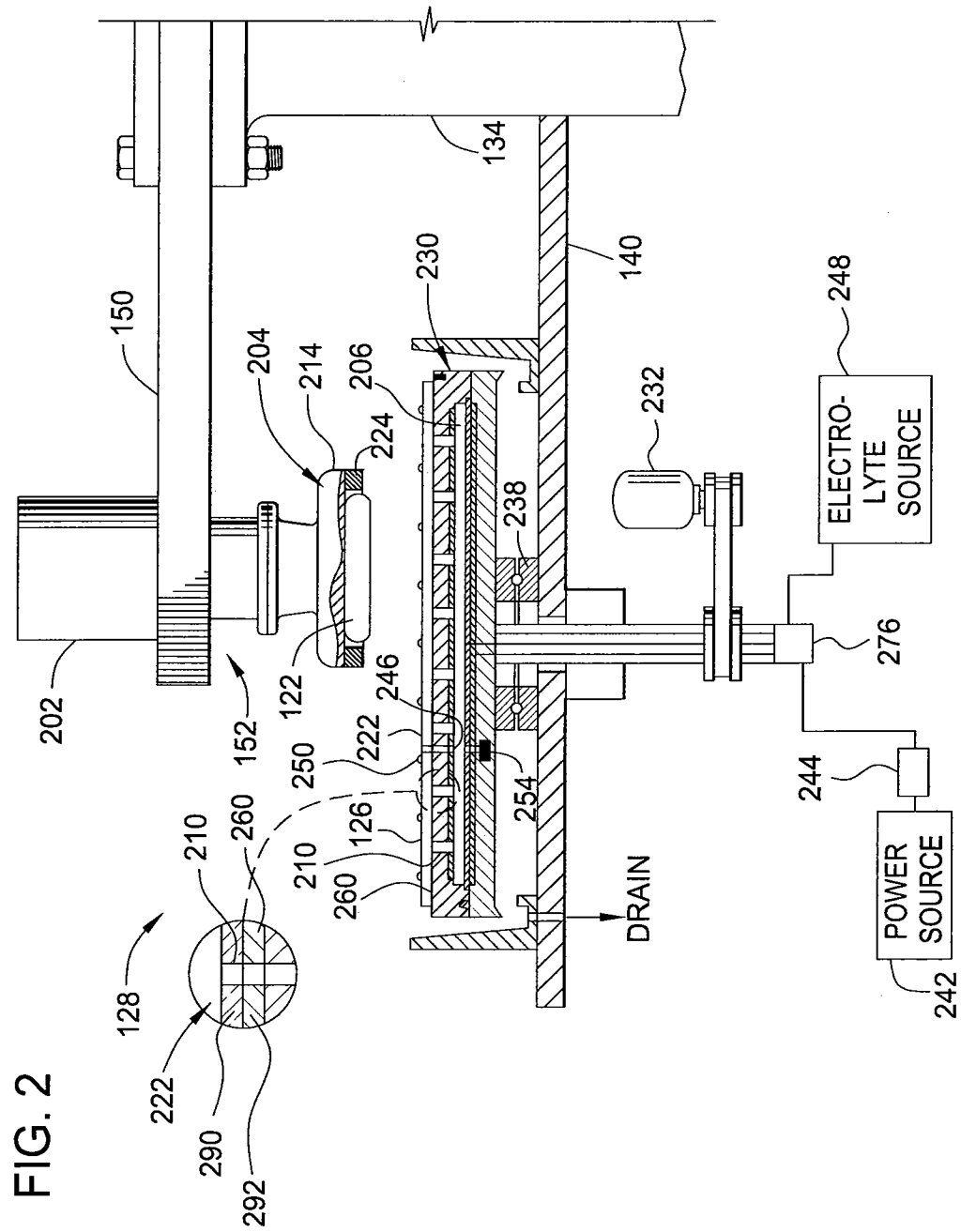
determining a change in projected processing time required to arrive at the target profile in at least one zone; and

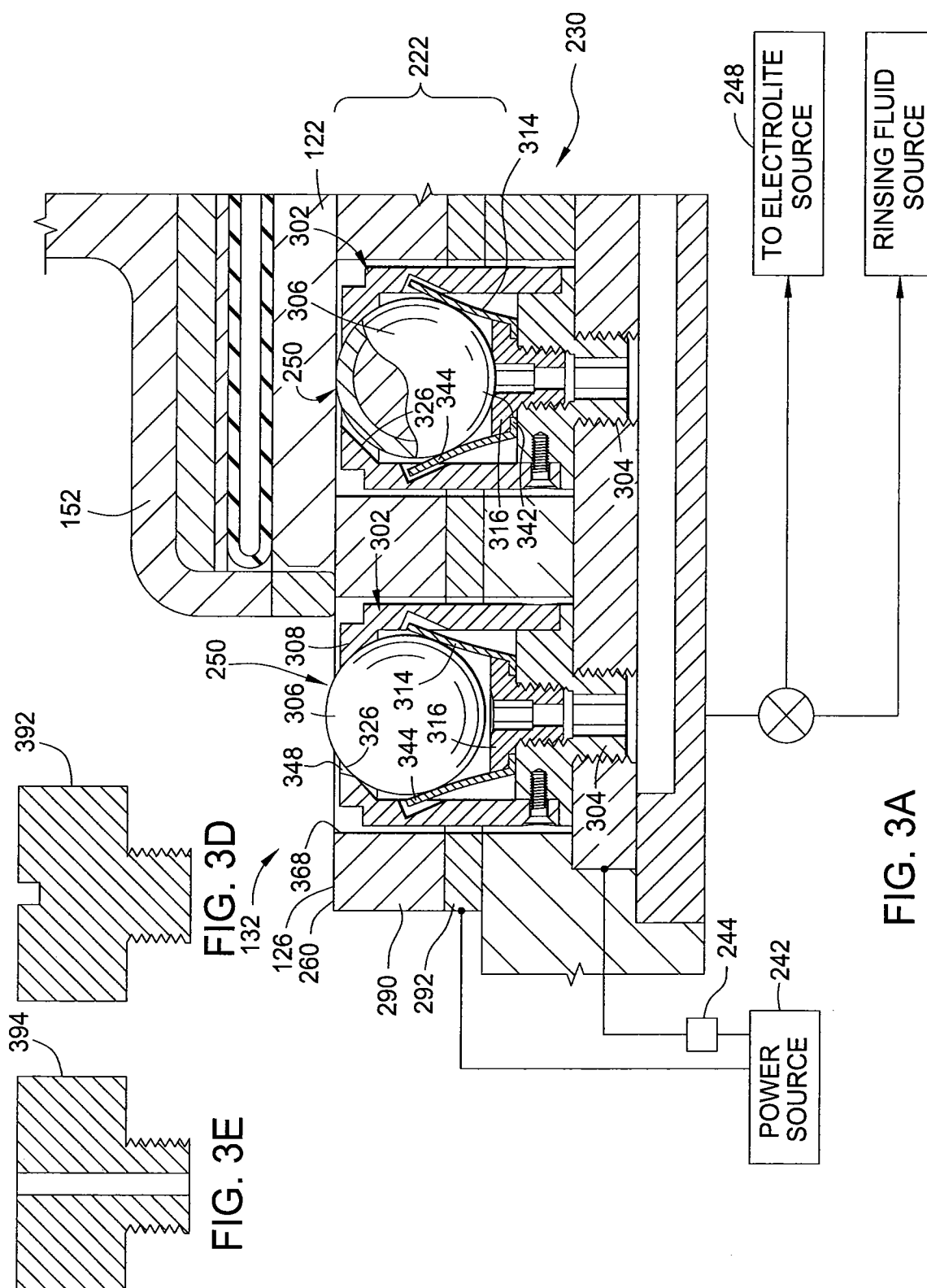
adjusting the electrochemical process to compensate for the determined change.

25. The method of claim 24, wherein adjusting the electrochemical process to compensate for the determined change further comprises:

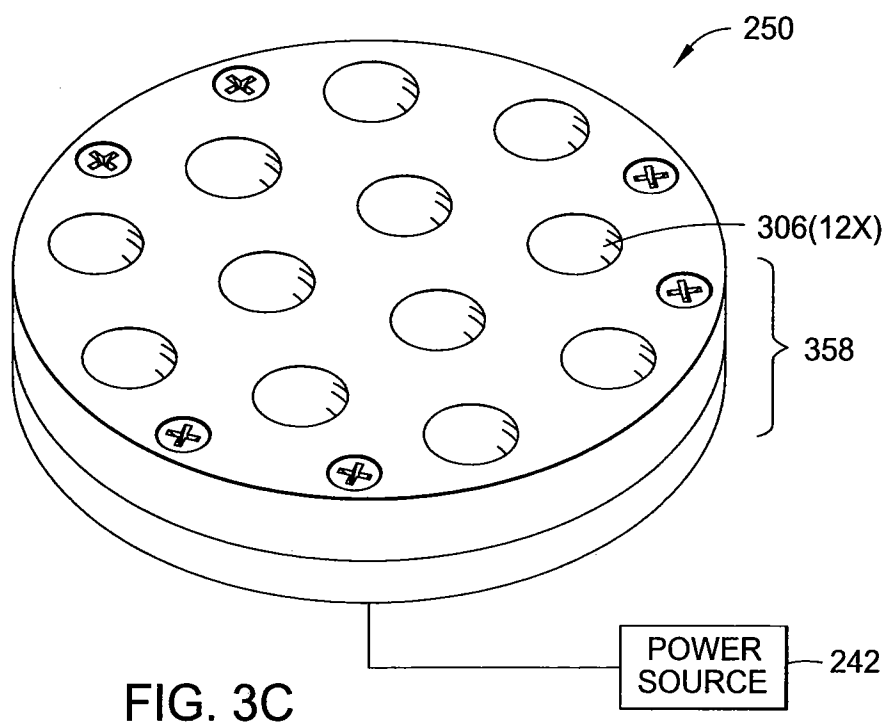
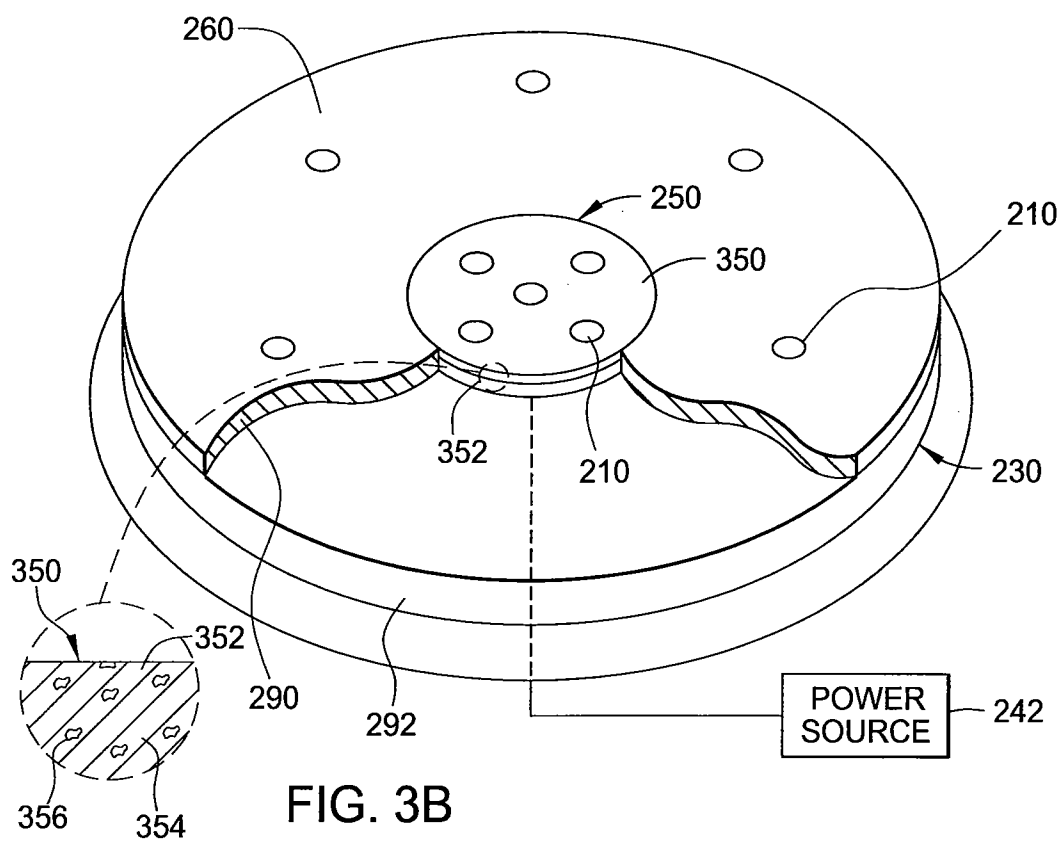
maintaining an offset in arrival at an endpoint between a fastest and slowest processing zone within a predetermined period.

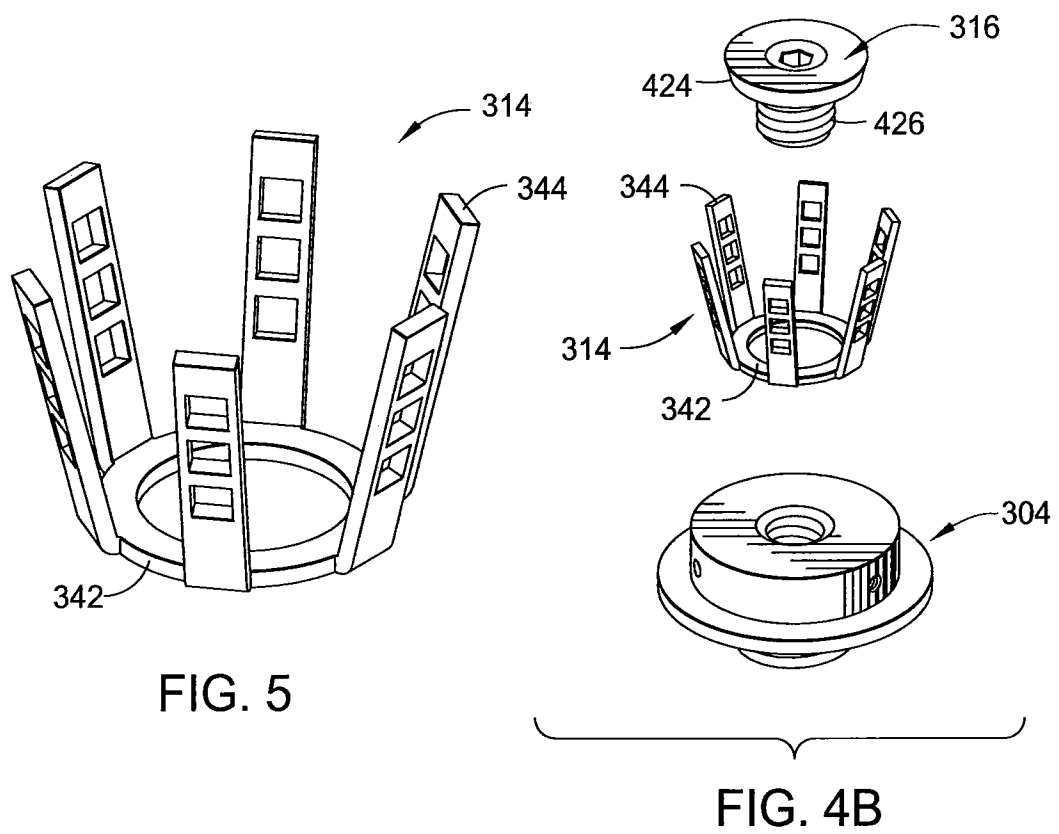
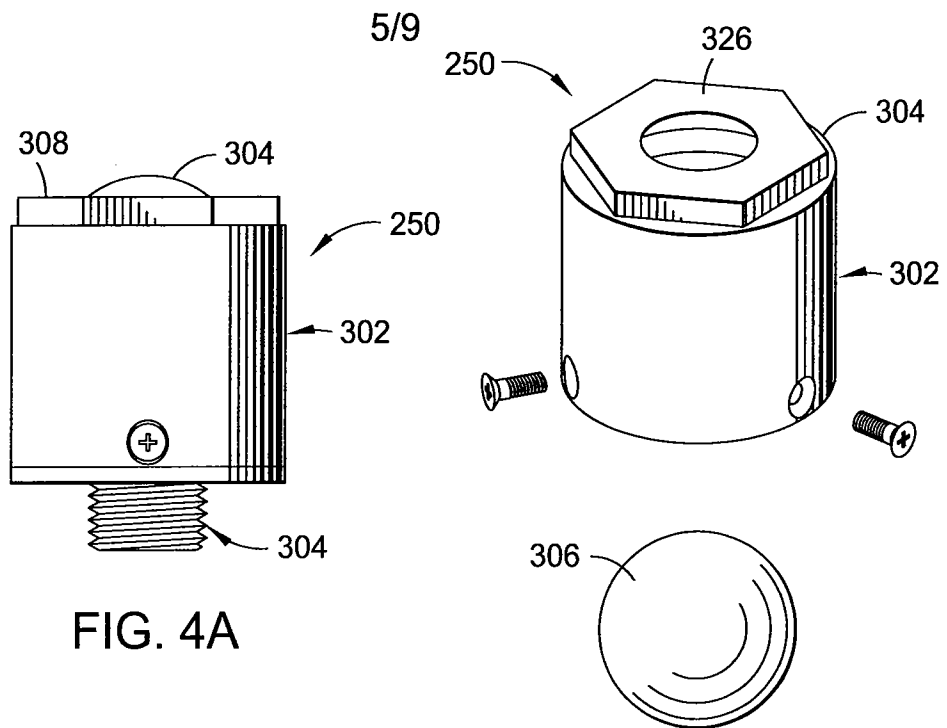


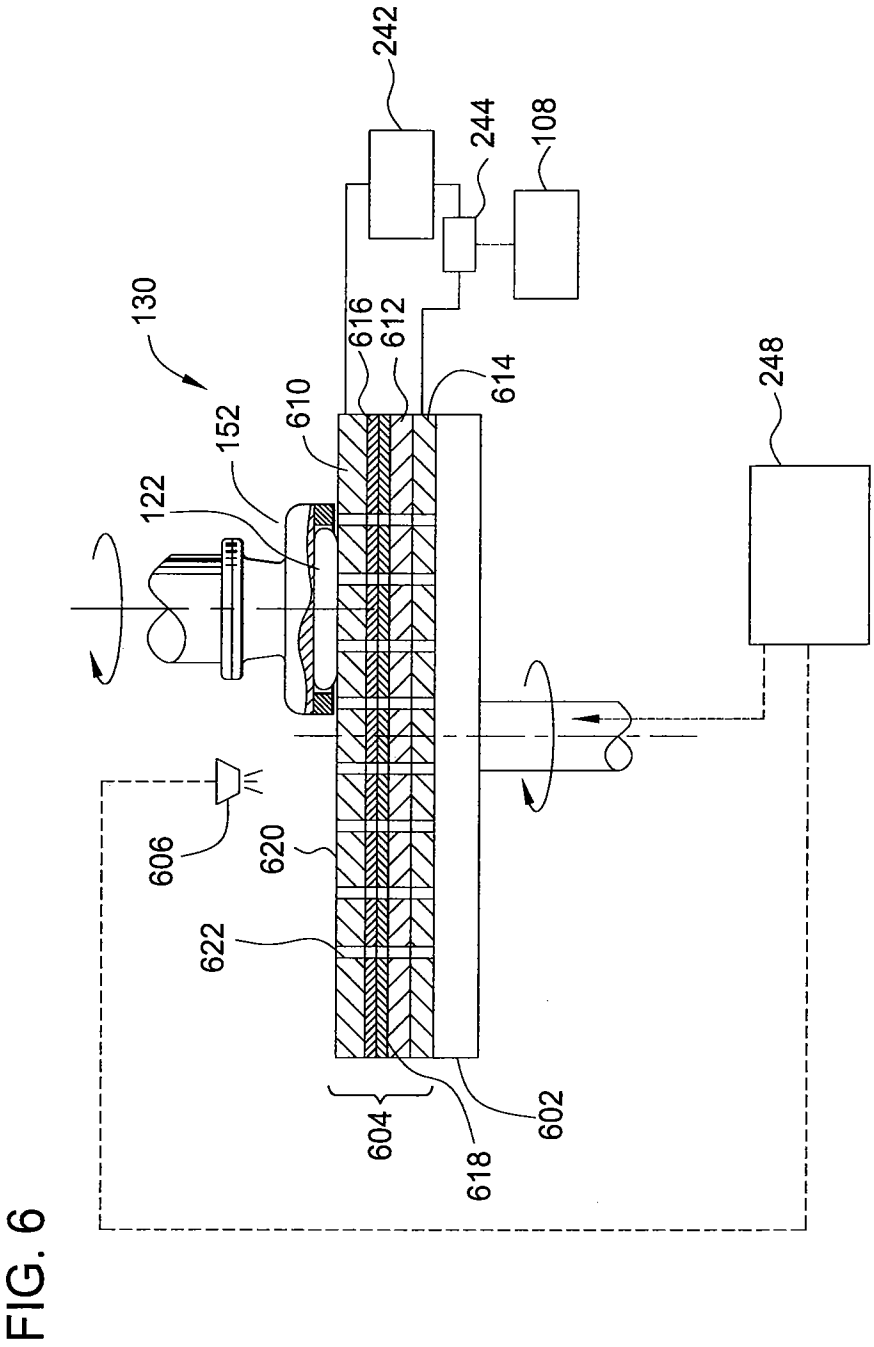




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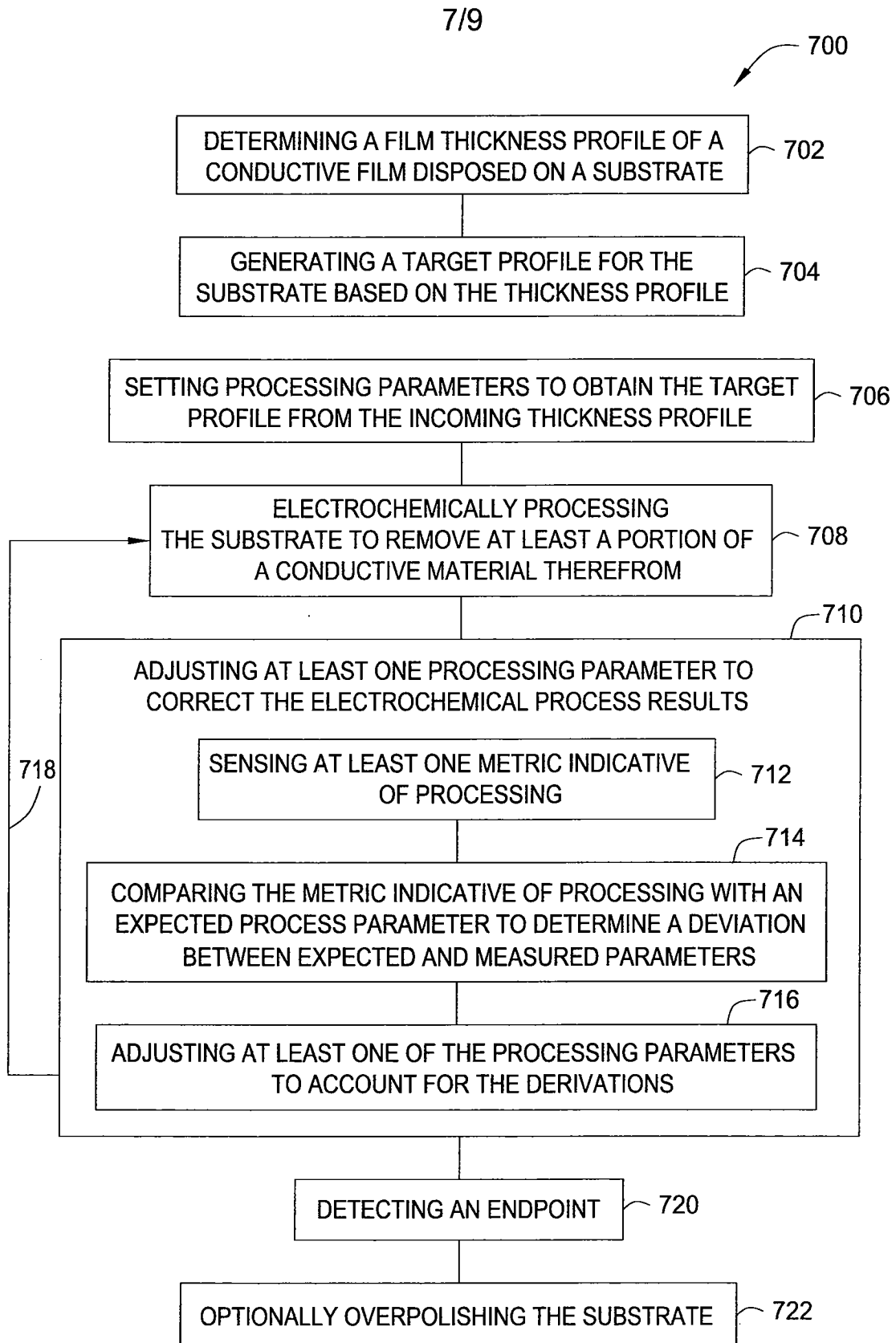


FIG. 7

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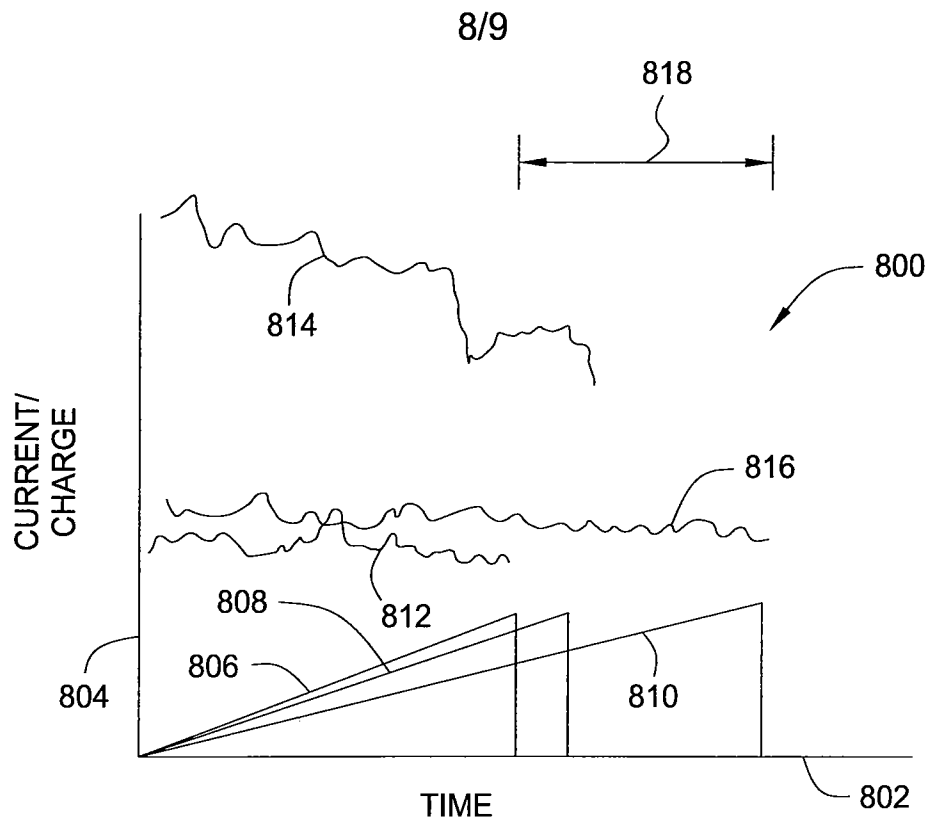


FIG. 8A

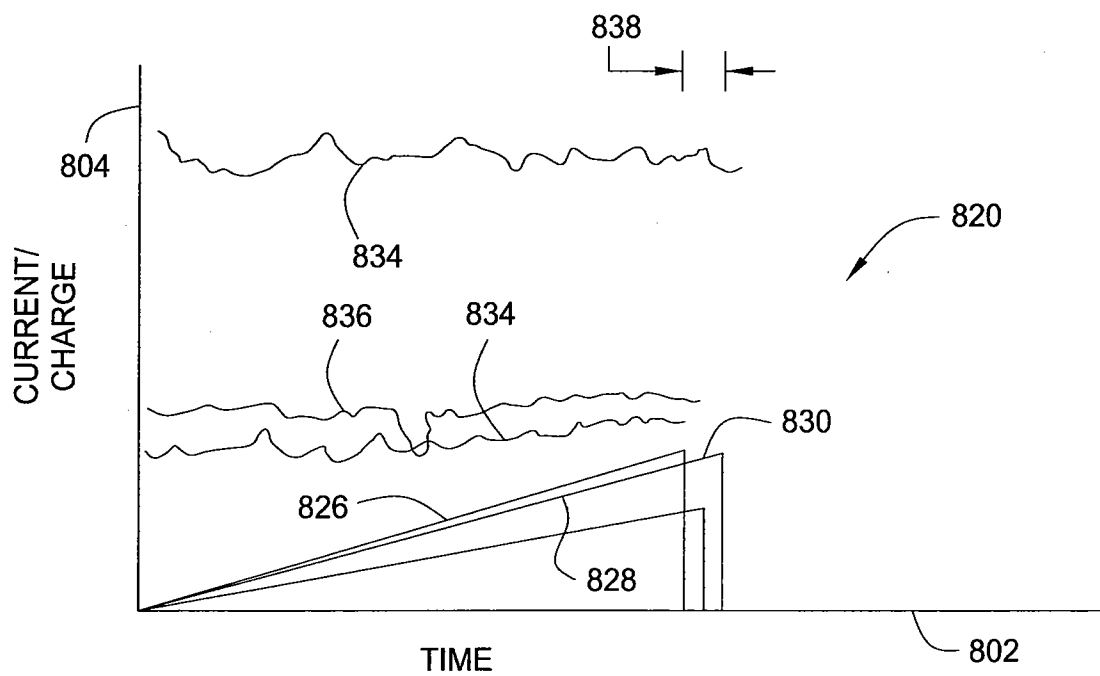


FIG. 8B

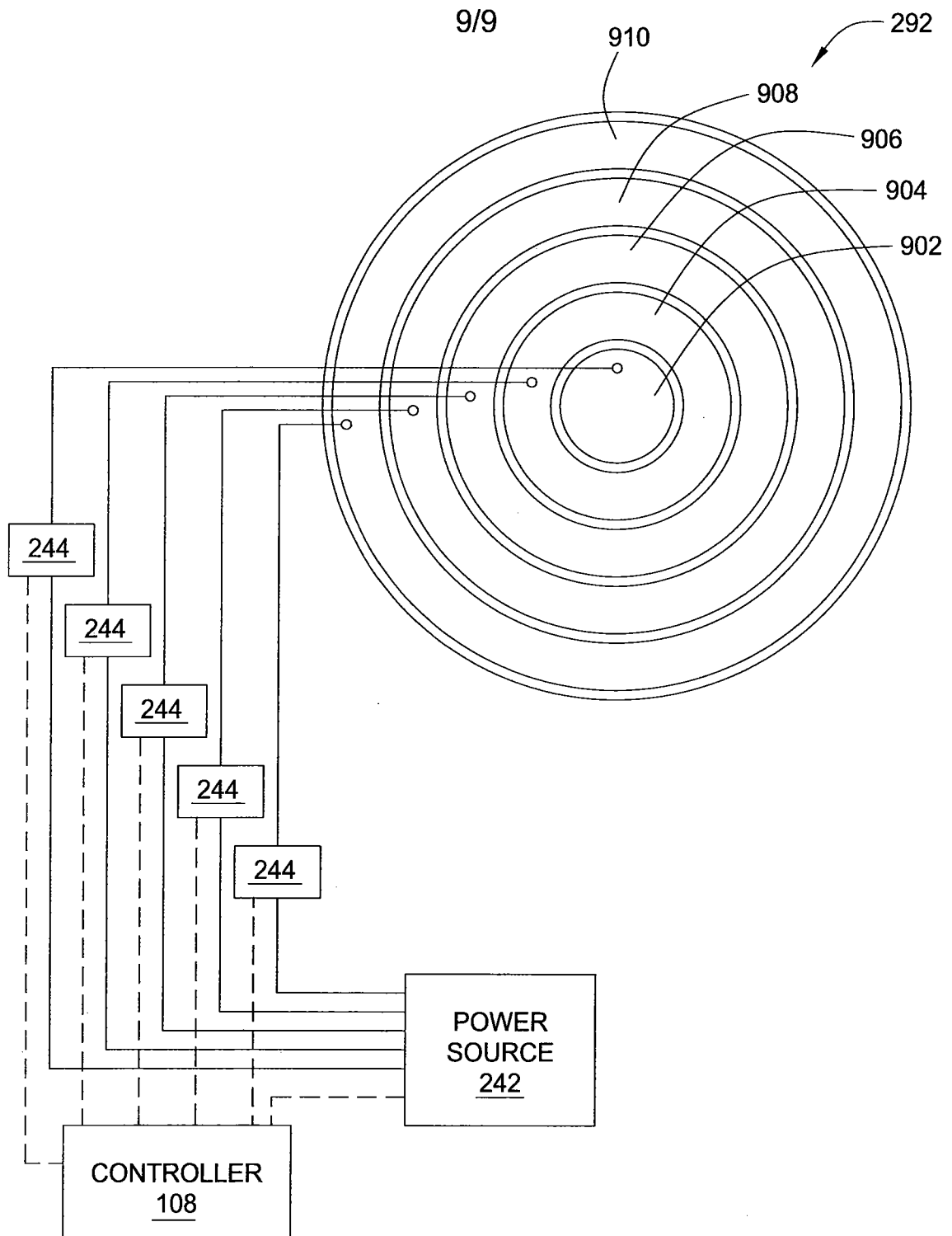


FIG. 9