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(54) **ELECTROPLATING APPARATUS WITH SEGMENTED ANODE ARRAY**

(76) Inventors: **Daniel J. Woodruff**, Kalispell, MT (US); **Kyle M. Hanson**, Kalispell, MT (US)

Correspondence Address:
PERKINS COIE LLP
P.O. BOX 1247
PATENT-SEA
SEATTLE, WA 98111-1247 (US)

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Publication Classification

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(57) **ABSTRACT**

An electroplating apparatus includes a reactor vessel having a segmented anode array positioned therein for effecting electroplating of an associated workpiece such as a semiconductor wafer. The anode array includes a plurality of ring-like anode segments which are preferably positioned in concentric, coplanar relationship with each other. The anode segments can be independently operated to create varying electrical potentials with the associated workpiece to promote uniform deposition of electroplated metal on the surface of the workpiece.

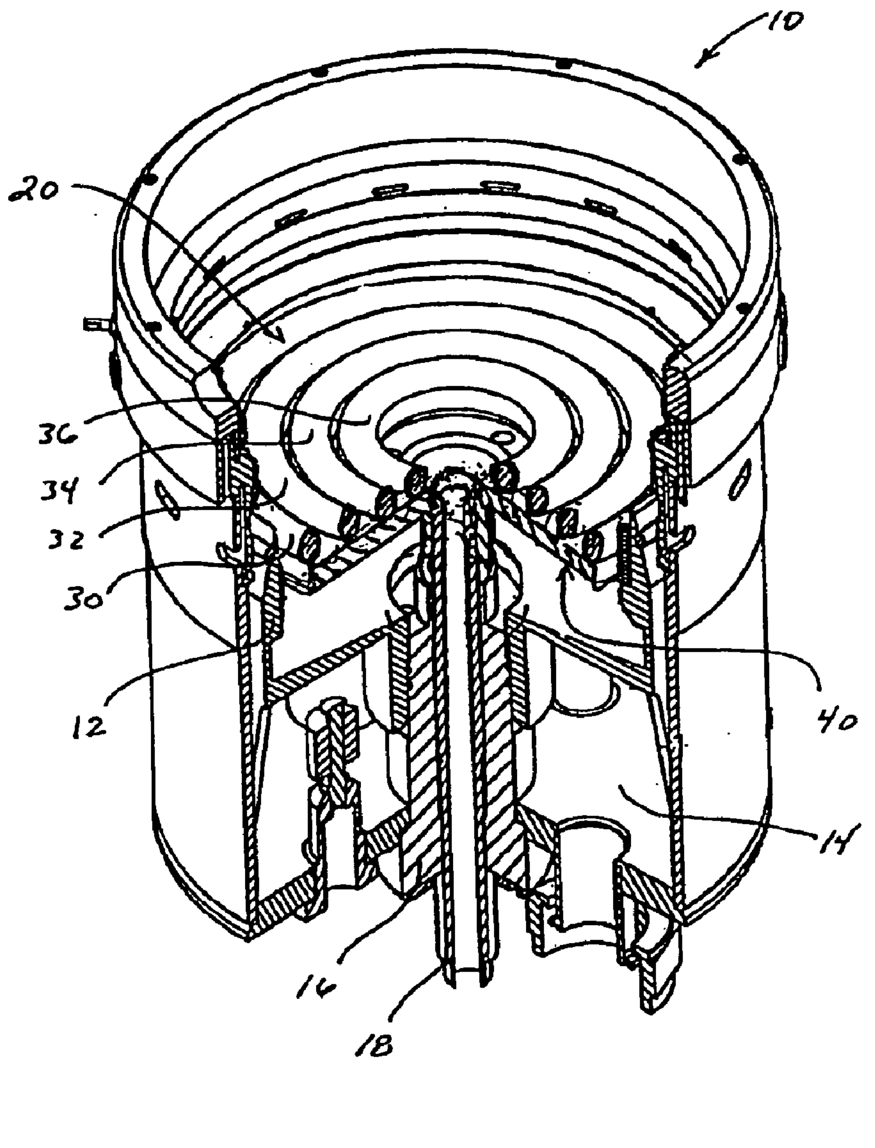


FIG_1

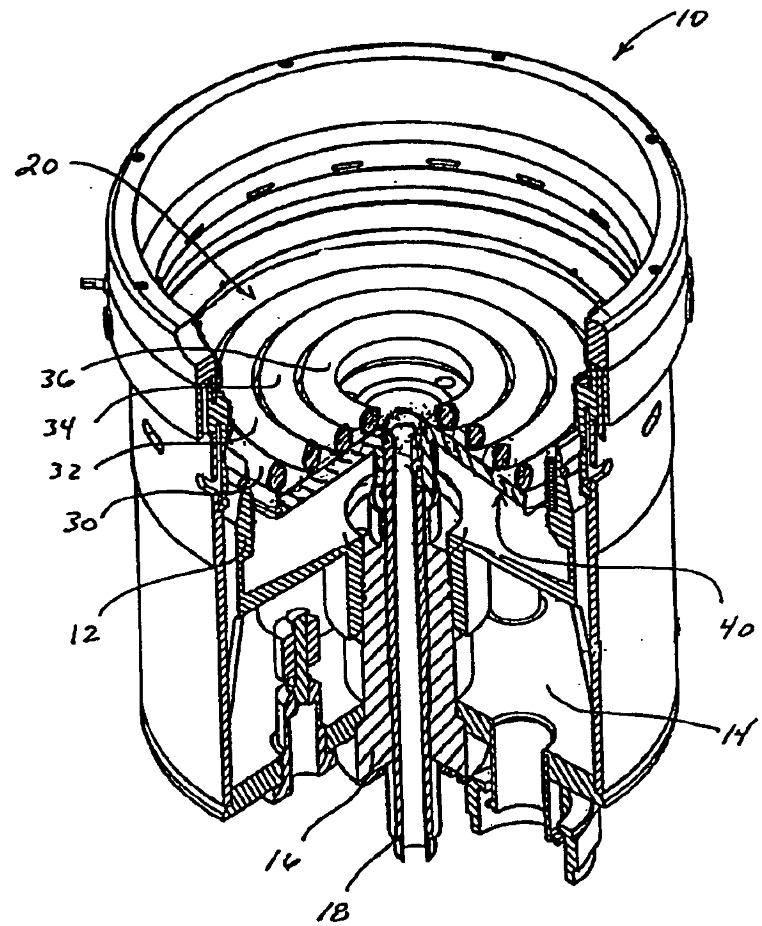


FIG_1a

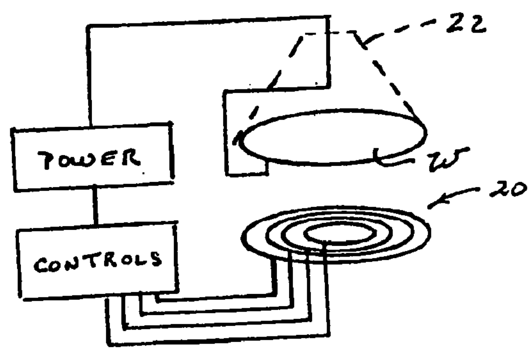


FIG_2

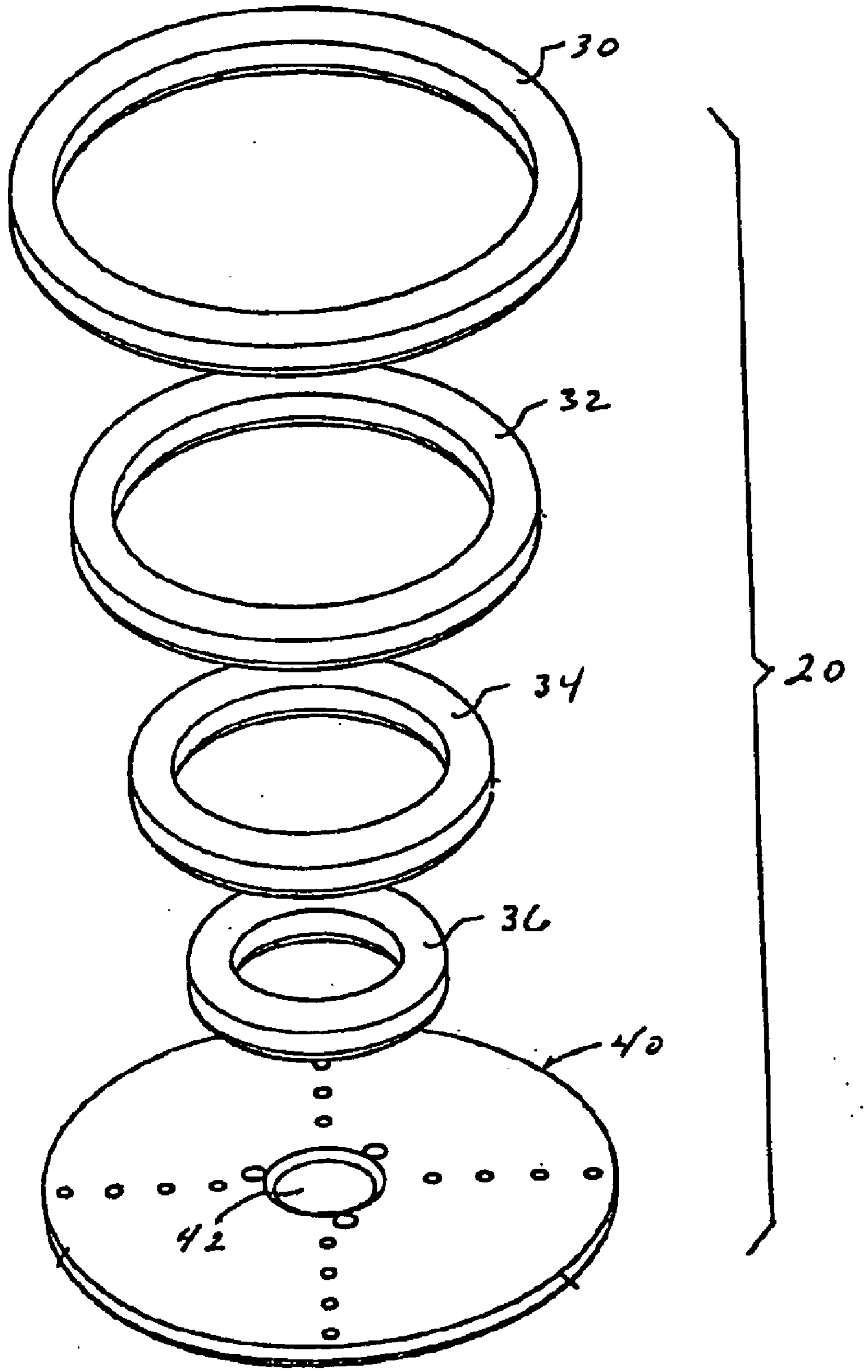


FIG_3

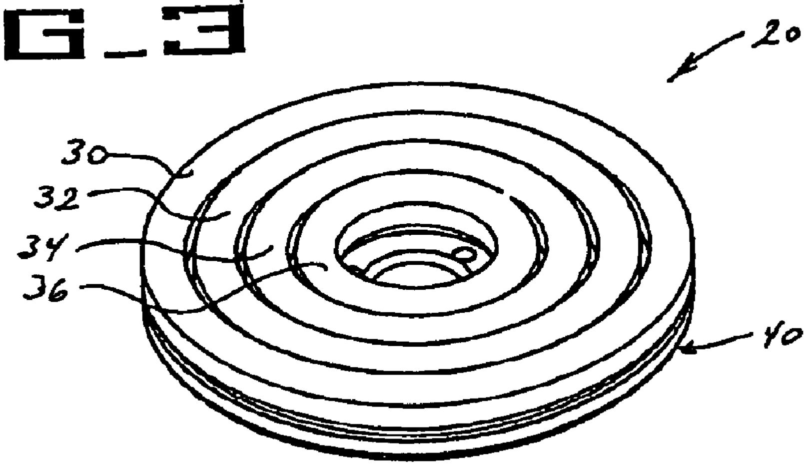


FIG_4

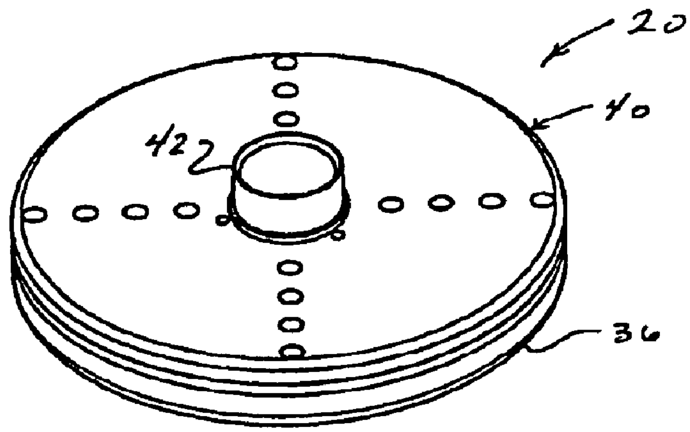


FIG_5

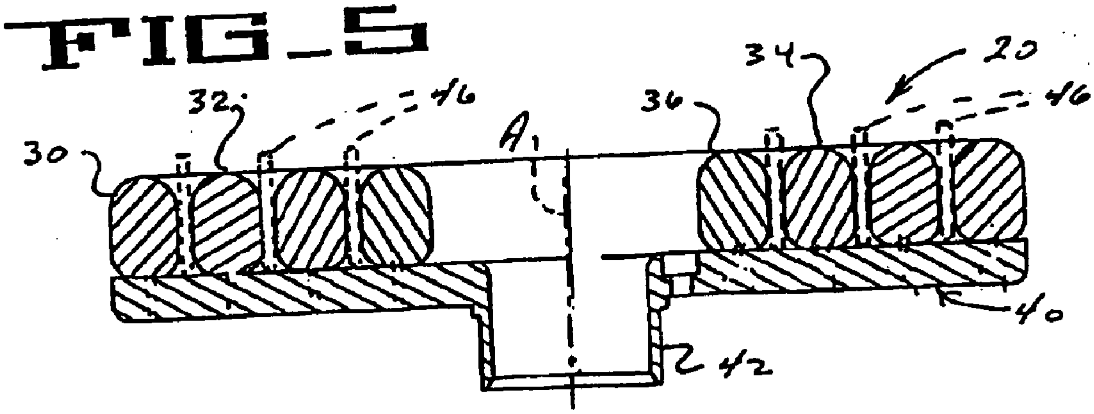


FIG. 6

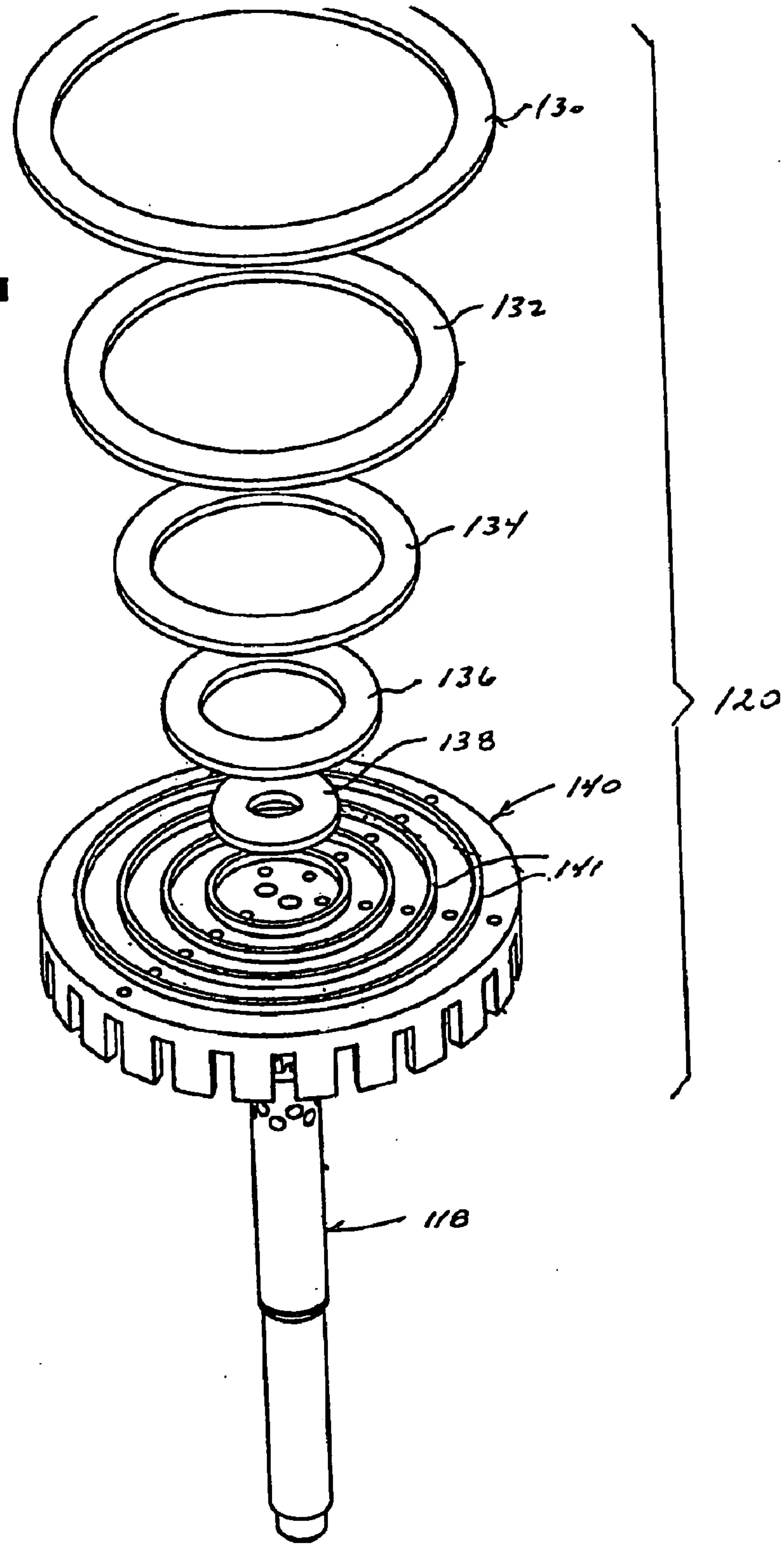


FIG_7

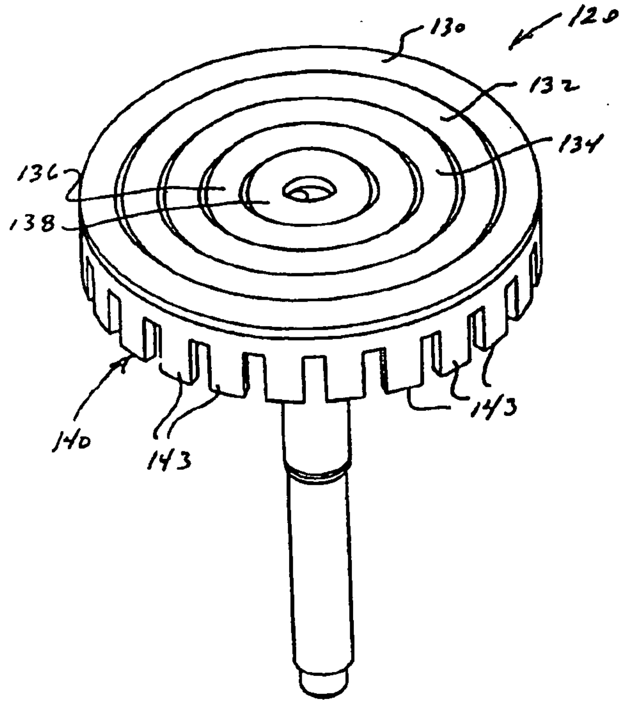


FIG_8

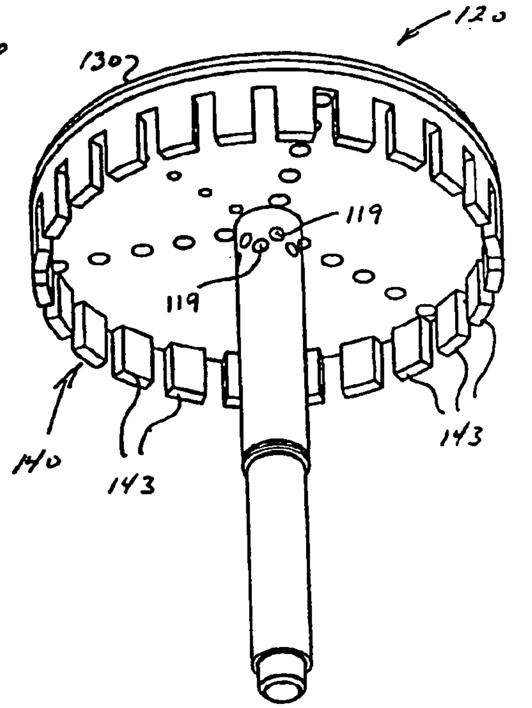
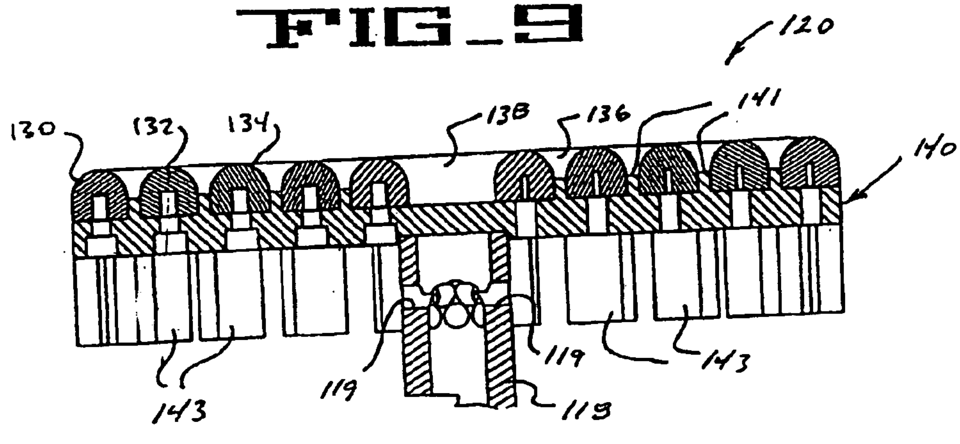


FIG_9



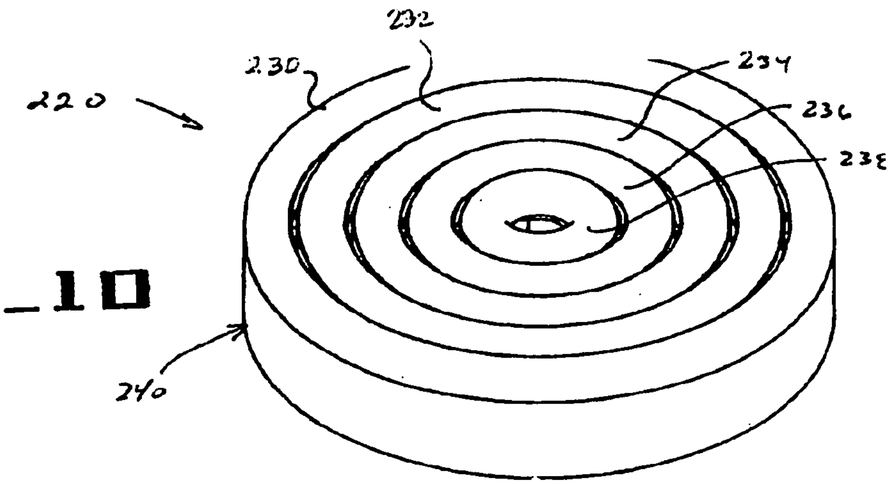


FIG_10

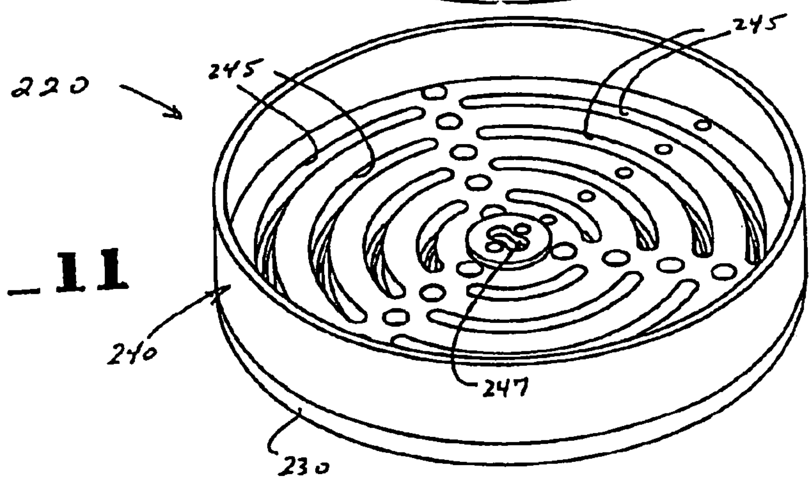


FIG_11

FIG_12

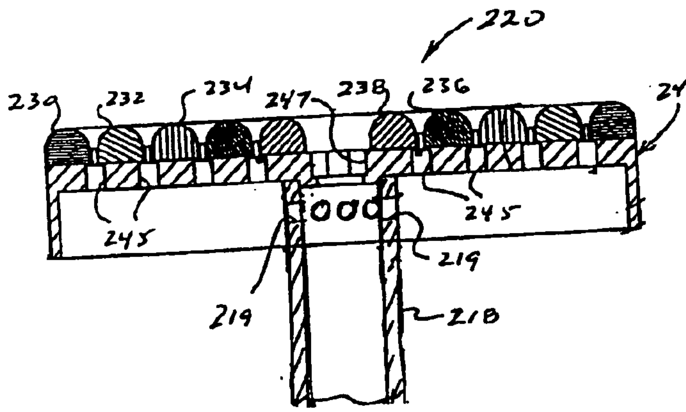


FIG_13

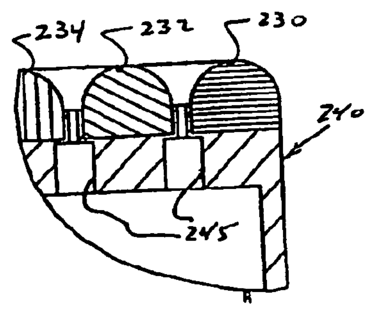
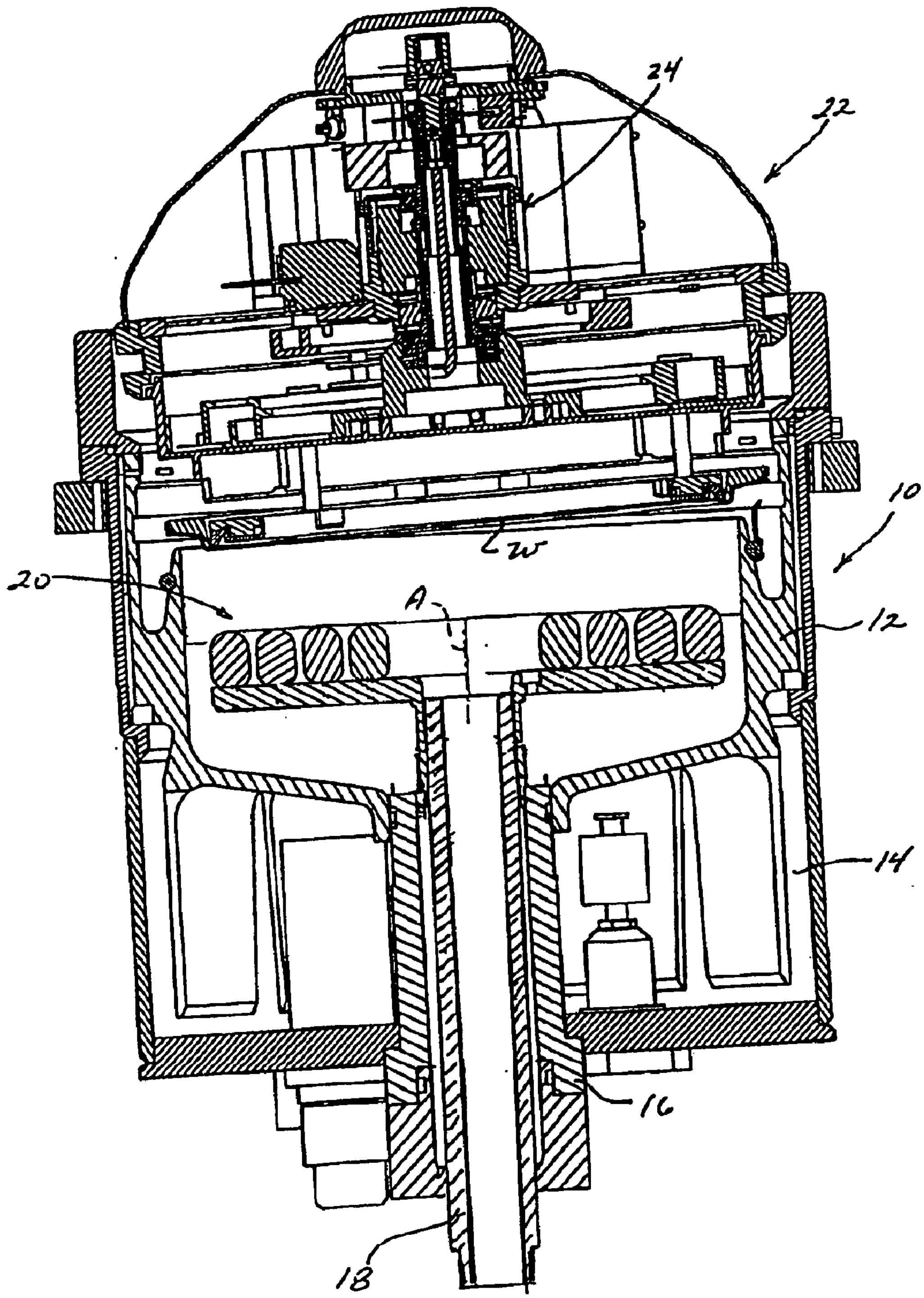


FIG_14



ELECTROPLATING APPARATUS WITH SEGMENTED ANODE ARRAY

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not Applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

BACKGROUND OF THE INVENTION

[0003] The present invention relates generally to an electroplating apparatus for plating of semiconductor components, and more particularly to an electroplating apparatus, including a segmented anode array comprising a plurality of concentrically arranged anode segments which can be independently operated to facilitate uniform deposition of electroplated metal on an associated workpiece.

[0004] Production of semiconductive integrated circuits and other semiconductive devices from semiconductor wafers typically requires formation of multiple metal layers on the wafer to electrically interconnect the various devices of the integrated circuit. Electroplated metals typically include copper, nickel, gold and lead. Electroplating is effected by initial formation of a so-called seed layer on the wafer in the form of a very thin layer of metal, whereby the surface of the wafer is rendered electrically conductive. This electroconductivity permits subsequent formation of a so-called blanket layer of the desired metal by electroplating in a reactor vessel. Subsequent processing, such as chemical, mechanical planarization, removes unwanted portions of the metal blanket layer formed during electroplating, resulting in the desired patterned metal layer in a semiconductor integrated circuit or micro-mechanism being formed. Formation of a patterned metal layer can also be effected by electroplating.

[0005] Subsequent to electroplating, the typical semiconductor wafer or other workpiece is subdivided into a number of individual semiconductor components. In order to achieve the desired formation of circuitry within each component, while achieving the desired uniformity of plating from one component to the next, it is desirable to form each metal layer to a thickness which is as uniform as possible across the surface of the workpiece. However, because each workpiece is typically joined at the peripheral portion thereof in the circuit of the electroplating apparatus (with the workpiece typically functioning as the cathode), variations in current density across the surface of the workpiece are inevitable. In the past, efforts to promote uniformity of metal deposition have included flow-controlling devices, such as diffusers and the like, positioned within the electroplating reactor vessel in order to direct and control the flow of electroplating solution against the workpiece.

[0006] In a typical electroplating apparatus, an anode of the apparatus (either consumable or non-consumable) is immersed in the electroplating solution within the reactor vessel of the apparatus for creating the desired electrical potential at the surface of the workpiece for effecting metal deposition. Previously employed anodes have typically been generally disk-like in configuration, with electroplating solution directed about the periphery of the anode, and through a perforate diffuser plate positioned generally above, and in spaced relationship to, the anode. The electroplating solution flows through the diffuser plate, and against the associated workpiece held in position above the diffuser. Uniformity of metal deposition is promoted by rotatably driving the workpiece as metal is deposited on its surface.

[0007] The present invention is directed to an electroplating apparatus having a segmented anode array, including a plurality of anode segments which can be independently operated at different electrical potentials to promote uniformity of deposition of electroplated metal on a associated workpiece.

BRIEF SUMMARY OF THE INVENTION

[0008] An electroplating apparatus embodying the principles of the present invention includes an electroplating reactor vessel which contains a segmented anode array immersed in electroplating solution held by the vessel. The anode array includes differently dimensioned anode segments, preferably comprising concentrically arranged ring-like elements, with the anode segments being independently operable at different electrical potentials. The flow of electroplating solution about the anode segments is controlled in conjunction with independent operation of the segments, with uniformity of electroplated metal deposition on the workpiece thus promoted.

[0009] In accordance with the illustrated embodiments, the present electroplating apparatus includes an electroplating reactor including a alike reactor vessel for holding electroplating solution. A segmented anode array in accordance with the present invention is positioned in the reactor vessel for immersion in the plating solution. The electroplating apparatus includes an associated rotor assembly which can be positioned generally on top of the electroplating reactor, with the rotor assembly configured to receive and retain an associated workpiece such as a semiconductor wafer. The rotor assembly is operable to position the workpiece in generally confronting relationship with the anode array, with the surface of the workpiece in contact with the electroplating solution for effecting deposition of metal on the workpiece. The reactor vessel defines an axis, with the workpiece being positionable in generally transverse relationship to the axis.

[0010] The anode array comprises a plurality of anode segments having differing dimensions, with the array being operable to facilitate uniform deposition of electroplated metal on the workpiece. In accordance with the illustrated embodiment, the segmented anode array is positioned generally at the lower extent of the reactor vessel in generally perpendicular relationship to the axis defined by the vessel. The anode array comprises a plurality of ring-like, circular anode segments arranged in concentric relationship to each other about the axis. Thus, at least one of the anode segments having a relatively greater dimension is positioned further from the axis than another one of the anode segments having a relatively lesser dimension. In the illustrated embodiment, each of the anode segments is configured to have an annular, ring-shape, with each being generally toroidal. It is presently preferred that the anode segments be generally coplanar, although it will be appreciated that the segments can be otherwise arranged.

[0011] The anode array includes a mounting base upon which the ring-like anode segments are mounted. The present invention contemplates various arrangements for directing and controlling flow of the associated electroplating solution. In particular, the mounting base can define at least one flow passage for directing flow of electroplating solution through the mounting base. In one form, a centralmost one of the anode segments defines an opening aligned with the reactor vessel axis, with the flow passage defined by the mounting base being aligned with the opening in the central anode segment In another embodiment, flow passages defined by the mounting base are positioned generally between adjacent ones of the anode segments for directing flow of electroplating solution therebetween. In this embodiment, a plurality of flow passages are provided which are arranged in a pattern of concentric circles to direct flow of electroplating solution between adjacent ones of the concentrically arranged anode segments.

[0012] In an alternate embodiment, the mounting base includes a plurality of depending, flow-modulating projections, defining flow channels therebetween, with the projections arranged generally about the periphery of the mounting base. In the preferred form, the present electroplating apparatus includes a control arrangement operatively connected to the segmented anode array for independently operating the plurality of anode segments. This permits the segments to be operated at different electrical potentials, and for differing periods of time, to facilitate uniform deposition of electroplated metal on the associated workpiece. The present invention contemplates that dielectric elements can also be positioned between at least two adjacent ones of the anode segments for further facilitating uniform deposition of electroplated metal on the workpiece.

[0013] Other features and advantages of the present invention will become readily apparent from the following detailed description, the accompanying drawings, and the appended claims

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0014] **FIG. 1** is a perspective view, in partial cross-section, of an electroplating reactor of an electroplating apparatus, including a segmented anode array, embodying the principles of the present invention;

[0015] **FIG. 1***a* is a diagrammatic view of a control system for the present electroplating apparatus;

[0016] **FIG. 2** is an exploded perspective view of the segmented anode array illustrated in **FIG. 1**;

[0017] **FIG. 3** is a top perspective view of the assembled anode array of **FIG. 2**;

[0018] **FIG. 4** is a bottom perspective view of the anode array illustrated in **FIG. 3**;

[0019] **FIG. 5** is a cross-sectional view of the anode array illustrated in the preceding FIGURES;

[0020] **FIG. 6** is an exploded perspective view of an alternative embodiment of the present segmented anode array;

[0021] **FIG. 7** is a top perspective view of the assembled segmented anode array illustrated in **FIG. 6**;

[0022] **FIG. 8** is a bottom perspective view of the anode array illustrated in **FIG. 7**;

[0023] **FIG. 9** is a cross-sectional view of the segmented anode array illustrated in **FIGS. 6-8**;

[0024] **FIG. 10** is a top perspective view of a further alternative embodiment of the present segmented anode array;

[0025] **FIG. 11** is a bottom perspective view of the segmented anode array shown in **FIG. 10**;

[0026] **FIG. 12** is a cross-sectional view of the segmented anode array shown in **FIGS. 11 and 12**;

[0027] **FIG. 13** is a relatively enlarged, fragmentary cross-sectional view of the segmented anode array shown in **FIG. 12**; and

[0028] **FIG. 14** is a diagrammatic view of the present electroplating apparatus, with a rotor assembly and associated reactor positioned together for workpiece processing

DETAILED DESCRIPTION OF THE INVENTION

[0029] While the present invention is susceptible of embodiment in various forms, there is shown in the drawings and will hereinafter be described presently preferred embodiments, with the understanding that the present disclosure is to be considered as an exemplification of the invention, and is not intended to limit the invention to the specific embodiments illustrated.

[0030] With reference first to **FIG. 1**, therein is illustrated an electroplating reactor **10** of an electroplating apparatus embodying the present invention. This type of electroplating apparatus is particularly suited for electroplating of semiconductor wafers or like workpieces, whereby an electrically conductive seed layer of the wafer is electroplated with a metallic blanket or patterned layer.

[0031] The electroplating reactor **10** is that portion of the apparatus which generally contains electroplating solution, and which directs the solution against a generally downwardly facing surface of an associated workpiece, W, to be plated (see **FIG. 14**). To this end, the reactor **10** includes a reactor vessel or cup **12** through which electroplating solution is circulated. Attendant to solution circulation, the solution flows from the reactor vessel **12**, over the weir-like periphery of the vessel, into a lower overflow chamber **14** of the reactor **10**. Solution is drawn from the overflow chamber typically to be replenished for re-circulation through the reactor.

[0032] Reactor **10** includes a riser tube **16**, within which an inlet conduit **18** is positioned for introduction of electroplating solution into the reactor vessel. A segmented anode array **20**, embodying the principles of the present invention, is positioned generally at the upper extent of the inlet conduit **18** in a manner, as will be further described, which promotes flow of electroplating solution over and about the anode array **20**. During processing, a rotor assembly **22** (**FIG. 14**) which receives and holds a workpiece W for electroplating, is positioned in cooperative association with reactor **10** such that the workpiece W is positioned in generally confronting relationship to the anode array **20**. As will be observed, the reactor vessel **12** defines an axis "A"

(**FIG. 14**), with the workpiece W positioned in generally transverse relationship to the axis. Similarly, the anode array **20** is positioned in generally transverse relationship to the axis "A", preferably perpendicular thereto. While the workpiece W may be positioned perpendicularly to the axis "A", the illustrated arrangement positions the workpiece W at an acute angle (such as on the order of 2°) relative to the surface of the electroplating solution within the reactor vessel **12** to facilitate venting of gas which can accumulate at the surface of the workpiece. During processing, the workpiece is rotatably driven by drive motor **24** of the rotor assembly for facilitating uniformity of deposition of electroplated metal on the workpiece surface.

[**0033**] With particular reference to **FIGS. 2-5**, the segmented anode array **20** includes a plurality of anode segments having differing dimensions, with at least one of the anode segments having a relatively greater dimension being positioned further from the axis of the reactor vessel than another one of the anode segments having a relatively lesser dimension. In particular, the anode segments comprise circular, ring-like elements, each of which is generally toroidal, and arranged in concentric relationship with each other. As is known in the art, the anode segments may be consumable, whereby metal ions of the anode segments are transported by the electroplating solution to the electrically conductive surface of the associated workpiece, which functions as a cathode.

[**0034**] In this illustrated embodiment, the segmented anode array **20** includes four (4) anode segments, respectively designated **30**, **32**, **34** and **36**. The anode segments are of relatively decreasing diameters, with the segments thus fitting one-within-the-other.

[**0035**] It is preferred that the anode segments be positioned in generally coplanar relationship with each other, with the segments coaxial with each other along axis "A". In order to maintain the segments in this relative disposition, the anode array **20** includes a mounting base **40** upon which each of the anode segments is mounted. The mounting base **40** includes a collar portion **42** which defines a flow passage for directing flow of electroplating solution through the mounting base. In this embodiment, the central-most one of the concentric anode segments defines an opening aligned with the axis "A" of the reactor vessel, with the flow passage defined by the collar portion of the mounting base **40** being aligned with the opening defined by this central-most one **36** of the anode segments.

[**0036**] Operation of this embodiment of the present invention contemplates that plating solution is pumped through inlet conduit **18**, through the flow passage defined by collar portion **42** of mounting base **40**, and through the center of the anode array so that the solution impinges upon the surface of the workpiece W. The plating rate at the surface of the workpiece ordinarily will vary radially due to the effect of the impinging solution on the hydrodynamic boundary layer. Compensation of this radial effect can be achieved by operating the anode segments at different electrical potentials. Such an arrangement is diagrammatically illustrated in **FIG. 1***a*, wherein controls of the present electroplating apparatus include suitable wiring for independently operating the plurality of segments of the anode array **20**. It is contemplated that not only can the various anode segments be operating at differing electrical potentials, they may also be operated for differing periods of time to optimize the uniformity of plating on the workpiece.

[**0037**] In addition to affecting plating uniformity by using different anode potentials, it is within the purview of the present invention to affect uniformity by the disposition of dielectric (insulating) elements between adjacent ones of the anode segments. This is illustrated in phantom line in **FIG. 5**, wherein dielectric elements **46** are positioned between each adjacent pair of the anode segments **30**, **32**, **34** and **36**.

[**0038**] The geometry of the dielectric elements can be modified to provide the desired effect on plating. Relatively tall geometries, i.e., dielectric elements which project significantly above the associated anode segments, are believed to tend to limit interaction of adjacent ones of the anode segments, and can tend to collimate solution flow to the workpiece. In contrast, shorter or perforated geometries are believed to tend to increase anode segment interaction. While the illustrated embodiments of the present invention show the anode segments positioned in coplanar relationship with each other, and thus, in generally equidistant relationship to the workpiece W, it is believed that an increase or decrease in anode segment interaction can also be achieved by positioning the ring-like anode segments at varying distances from the surface of the workpiece.

[**0039**] Depending upon the type of electroplating process, the segments of the anode array may be either consumable, or non-consumable. For those applications requiring a consumable anode, the anode segments can be formed from copper, such as phosphorized copper. In contrast, nonconsumable anode segments can be formed from platinum plated titanium.

[**0040**] It is contemplated that suitable mechanical fasteners (not shown) be employed for individually securing each of the anode segments to the associated mounting base **40**. Additionally, suitable scaled wiring (not shown) is provided for individually electrically connecting each of the anode segments with associated controls of the electroplating apparatus, whereby the electrical potential created by each anode segment can be independently varied and controlled. In this embodiment, it is contemplated that no perforate diffuser member be employed positioned between the anode array **20** and the workpiece W. Solution flow rate and current distribution can be controlled independently of one another to optimize the plating process and promote uniformity of deposition of electroplated metal. Air bubbles introduced into the plating chamber by the incoming plating solution are flushed past the workpiece surface, and thus will not interfere with the plating process. Venting of the workpiece surface, by its angular disposition as discussed above, may also be effected. Solution flow from the center of the anode array insures that the workpiece surface will be wetted from the center to the periphery. This prevents air from being trapped at the center of the workpiece when it first contacts the surface of the solution.

[**0041**] As will be appreciated, the we of a segmented anode array having circular anode segments is particularly suited for use with circular, disk-like wafers or like workpieces. However, it is within the purview of the present invention that the anode array, including the anode segments, be non-circular.

[**0042**] With reference now to **FIGS. 6-9**, therein is illustrated an alternate embodiment of the present segmented anode array. In this embodiment, elements which generally correspond to those in the above-described embodiment are designated by like reference numerals in the one-hundred series.

[0043] Segmented anode array **120** includes a plurality of ring-like anode segments. In this embodiment, five (5) of the anode segments are provided in concentric relationship with each other, including segments **130**, **132**, **134**, **136** and **138**.

[0044] The anode array **120** includes a mounting base **140** having a plurality of divider elements **141** respectively positioned between adjacent ones of the circular anode segments. As in the previous embodiment, the anode segments are positioned in coplanar relationship with each other on the mounting base, and are positioned in coaxial relationship with the axis "A" of the associated reactor vessel.

[0045] In distinction from the previous embodiment, anode array **120** is configured such that flow of electroplating solution is directed generally about the periphery of the array. In particular, the mounting base **140** includes a plurality of circumferentially spaced depending flow-modulating projections **143** which define flow channels between adjacent ones of the projections. Electroplating solution is introduced into the reactor vessel through an inlet conduit **118**, which defines a plurality of flow passages **119** generally at the upper extent thereof, beneath mounting base **140**, and inwardly of flow-modulating projections **143**. The solution then flows between the flow-modulating projections, and upwardly generally about the anode segments.

[0046] This embodiment illustrates a series of openings defined by mounting base **140**. With particular reference to **FIG. 8**, those series of holes aligned at 120° intervals about the base portion are configured for receiving respective mechanical fasteners (not shown) for securing the anode segments to the mounting base. The remaining series of radially-spaced openings defined by the mounting base are provided for suitable electrical connection with each individual anode segment.

[0047] With reference to **FIGS. 10-13**, another alternate embodiment of the segmented anode array embodying the principles of the present invention is illustrated. Elements of this embodiment, which generally correspond to like elements in the previously described embodiment, are so-designated by like reference numerals in the two-hundred series.

[0048] Anode array **220** includes a plurality of circular, concentrically arranged ring-like anode segments **230**, **232**, **234**, **236** and **238**. The anode segments are positioned in coplanar relationship on a mounting base **240**. Notably, this configuration of the anode array is arranged to permit flow of electroplating solution between adjacent ones of the anode segments. To this end, the mounting base **240** defines a plurality of flow passages **245** arranged in a pattern of concentric circles to direct flow of electroplating solution between adjacent ones of the ring-like anode segments. An inlet conduit **218** defines a plurality of flow passages **219** so that plating solution can flow from the inlet conduit through the flow passages **245**. This embodiment also includes a flow passage **247** defined by the mounting base **240** for directing flow through an opening defined by the central-most one **238** of the anode segments.

[0049] From the foregoing, it will be observed that numerous modifications and variations can be effected without departing from the true spirit and scope of the novel concept of the present invention. It will be understood that no limitation with respect to the specific embodiments illustrated herein is intended or should be inferred. The disclosure is intended to cover, by the appended claims, all such modifications as fall within the scope of the claims.

1-16. (canceled)

17. A method for electrochemically processing a microelectronic workpiece, comprising:

contacting a surface of a workpiece with a liquid processing solution as the processing solution flows through a reactor vessel;

controlling electrical potentials applied independently to a plurality of separate electrodes such that individual electrodes establish field components of an electrical field in the processing solution; and

differing the electrical field in the processing solution over time to electrochemically process the surface of the workpiece.

18. The method of claim 17 wherein the plurality of electrodes comprise a first annular conductive element and a second annular conductive element concentric with the first annular conductive element, and wherein controlling the electrical potentials comprises applying a first electrical potential to the first annular conductive element and a second electrical potential to the second annular conductive element that is different than the first electrical potential.

19. The method of claim 18 wherein differing the electrical field comprises differing at least one of the first and second electrical potentials over the time of electrochemically processing the surface of the workpiece.

20. The method of claim 17 wherein controlling the electrical potentials comprises applying different electrical potentials to different electrodes and differing the electrical field comprises applying the different electrical potentials to the different electrodes at differing times over the time of electrochemically processing surface of the workpiece.

21. The method of claim 20 wherein the plurality of electrodes comprise a circular first conductive element and a circular second conductive element concentrically surrounding the first conductive element, and wherein controlling the electrical potentials comprises generating concentric field components in the electrical field.

22. A method for electrochemically processing a microelectronic workpiece, comprising:

contacting a surface of a workpiece with a liquid processing solution as the processing solution flows through a reactor vessel;

applying electrical potentials independently to a plurality of separate electrodes such that individual electrodes establish field components of an electrical field in the processing solution; and

compensating for radial affects on the workpiece by differing at least one of the field components over a time of electrochemically processing the surface of the workpiece.

23. The method of claim 22 wherein applying electrical potentials independently to the plurality of electrodes comprises applying different electrical potentials to different electrodes.

24. The method of claim 22 wherein differing at least one of the field components over the time of electrochemically processing the surface of the workpiece comprises differing at least one of the electrical potentials applied to one of the electrodes.

25. A method for electrochemically processing a microelectronic workpiece, comprising:

passing a liquid processing solution through a reactor vessel;

contacting a surface of the workpiece with the liquid processing solution;

establishing an electrical field in the liquid processing solution by independently operating a first electrode and a second electrode separate from the first electrode, wherein the first and second electrodes are in the reactor vessel; and

applying different electrical potentials to the first and second electrodes for different periods of time to electrochemically process the surface of the workpiece.

26. The method of claim 25 wherein applying different electrical potentials to the first and second electrodes for different periods of time comprises changing an electrical potential to at least one of the first and second electrodes over the time of electrochemically processing the surface of the workpiece.

27. A method for electrochemically processing a microelectronic workpiece, comprising:

contacting a surface of the workpiece with a liquid processing solution while passing the liquid processing solution through a reactor vessel;

independently operating a first electrode and a second electrode separate from the first electrode, wherein the first and second electrodes are in the reactor vessel and spaced apart from the workpiece; and

changing electrical potentials applied to the first and second electrodes to electrochemically process the surface of the workpiece.

28. A method for electrochemically processing a microelectronic workpiece, comprising:

contacting a surface of the workpiece with a liquid processing solution while passing the liquid processing solution through a reactor vessel;

applying a first electrical potential to a first electrode located in the reactor vessel and spaced apart from the workpiece;

applying a second electrical potential to a second electrode located in the reactor vessel and spaced apart from the workpiece, the second electrode being separate from the first electrode, and the second electrical potential being different than the first electrical potential; and

changing the first electrical potential and/or the second electrical potential to electrochemically process the surface of the workpiece.

29. An apparatus for electrochemically processing a microelectronic workpiece, comprising:

a reactor vessel having a container for holding a liquid processing solution;

an electrode array in the reactor vessel, the electrode array including a first electrode and a second electrode separate from the first electrode; and

a control arrangement operatively coupled to the electrode array, wherein the control arrangement is configured to (a) independently apply different electrical potentials to the first and second electrodes such that the first and second electrodes establish individual field components of an electrical field in the processing solution, and (b) differ the electrical field in the processing solution over time to electrochemically process the workpiece.

30. The apparatus of claim 29 wherein the first electrode comprises a first annular conductive member and the second electrode comprises a second annular conductive member concentric with the first annular conductive member to establish concentric field components in the electrical field.

31. The apparatus of claim 29 wherein the first electrode comprises a first annular conductive member, the second electrode comprises a second annular conductive member concentric with the first annular conductive member, and the electrode array further comprises an annular wall between the first and second annular conductive members.

32. The apparatus of claim 29 wherein the control arrangement is configured to differ the electrical field by differing at least one of the electrical potentials applied to one of the first and second electrodes over the time to electrochemically process the surface of the workpiece.

33. An apparatus for electrochemically processing a microelectronic workpiece, comprising:

a reactor vessel configured to contain a processing solution;

an electrode array having a plurality of separate electrodes in the reactor vessel;

electrical wiring connected to the separate electrodes and configured to independently provide electrical potentials to the separate electrodes; and

a controller operatively connected to the electrical wiring, the controller being configured to apply different electrical potentials to the separate electrodes at different periods of time via the electrical wiring to electrochemically process the workpiece.

34. The apparatus of claim 33 wherein the electrode array comprises a first annular conductive member and a second annular conductive member concentric with the first annular conductive member.

35. The apparatus of claim 34 further comprising an annular wall between the first annular conductive member and the second annular conductive member.

36. The apparatus of claim 34 wherein the controller is configured to change the electrical potentials applied to the first and second annular conductive members at different periods of time to plate onto the workpiece.

37. An apparatus for electrochemically processing a microelectronic workpiece, comprising:

a reactor vessel having a container for holding a liquid processing solution;

an electrode array in the reactor vessel, the electrode array including a first electrode and a second electrode separate from the first electrode; and a control arrangement operatively coupled to the electrode array, wherein the control arrangement is configured to operate the first and second electrodes independently at differing electrical potentials to electrochemically process the workpiece.

38. The apparatus of claim 37 wherein the control arrangement is configured to apply different electrical potentials to the first and second electrodes.

39. The apparatus of claim 37 wherein the first electrode comprises a first annular conductive member and the second electrode comprises a second annular conductive member concentric with the first annular conductive member.

40. The apparatus of claim 37 wherein the first electrode comprises a first annular conductive member, the second electrode comprises a second annular conductive member concentric with the first annular conductive member, and the electrode array further comprises an annular wall between the first and second annular conductive members.

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