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(54) CURRENT COLLIMATION FOR THIN SEED AND DIRECT PLATING

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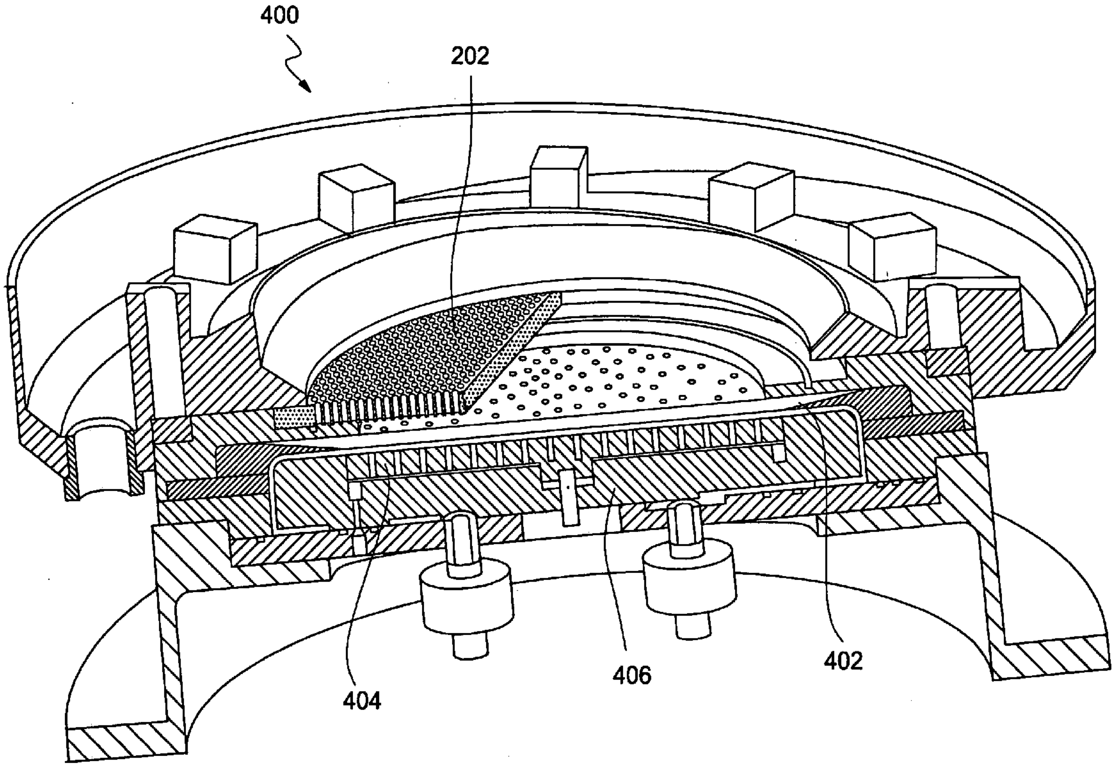
(57) ABSTRACT

A method and apparatus for plating a conductive material onto a substrate is provided. The apparatus includes a fluid processing cell having a fluid basin configured to contain an electrolyte solution and having an opening configured to receive a substrate for processing, an anode assembly positioned in the fluid basin, and a collimator positioned in the fluid basin between the anode assembly and the opening.



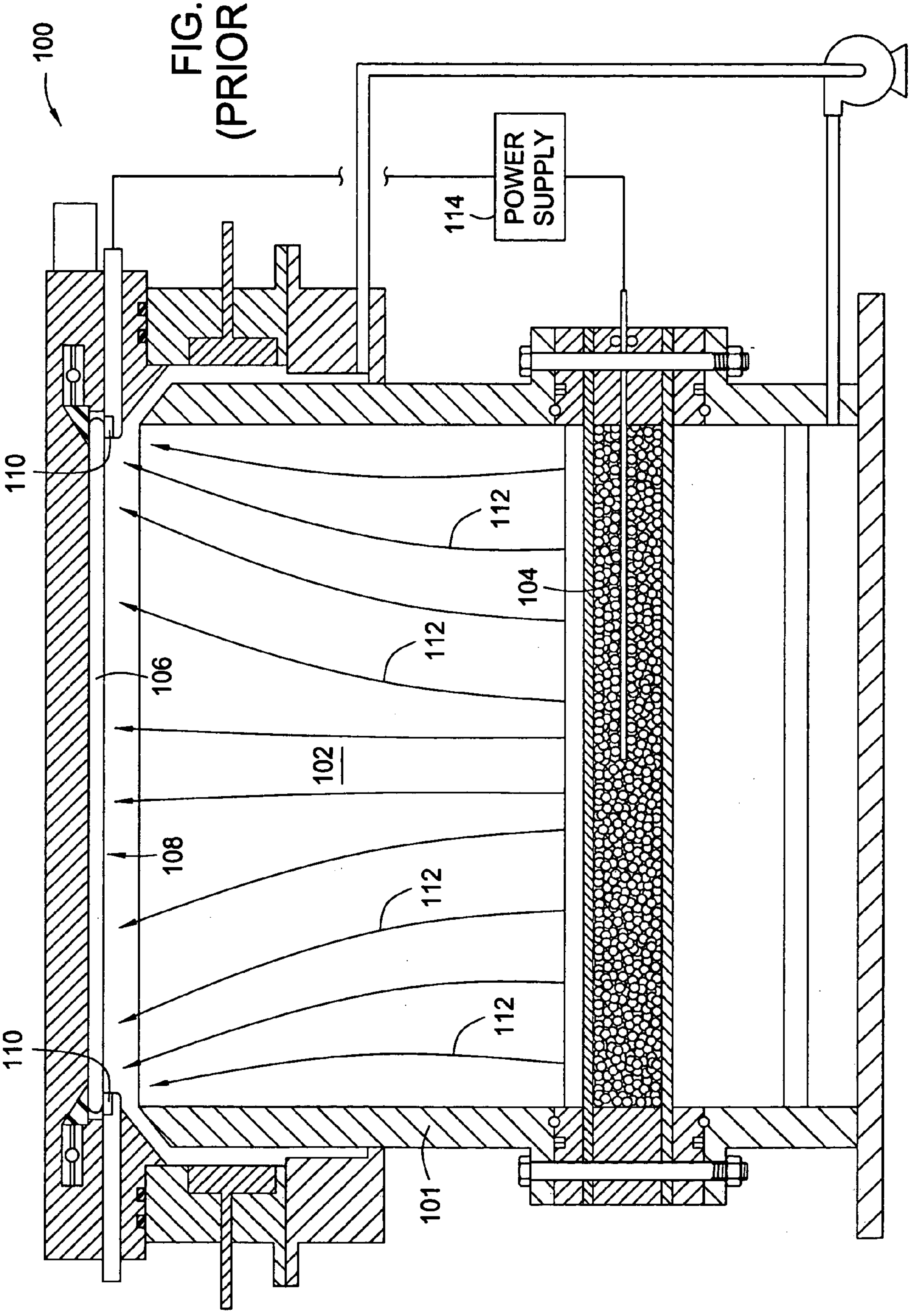
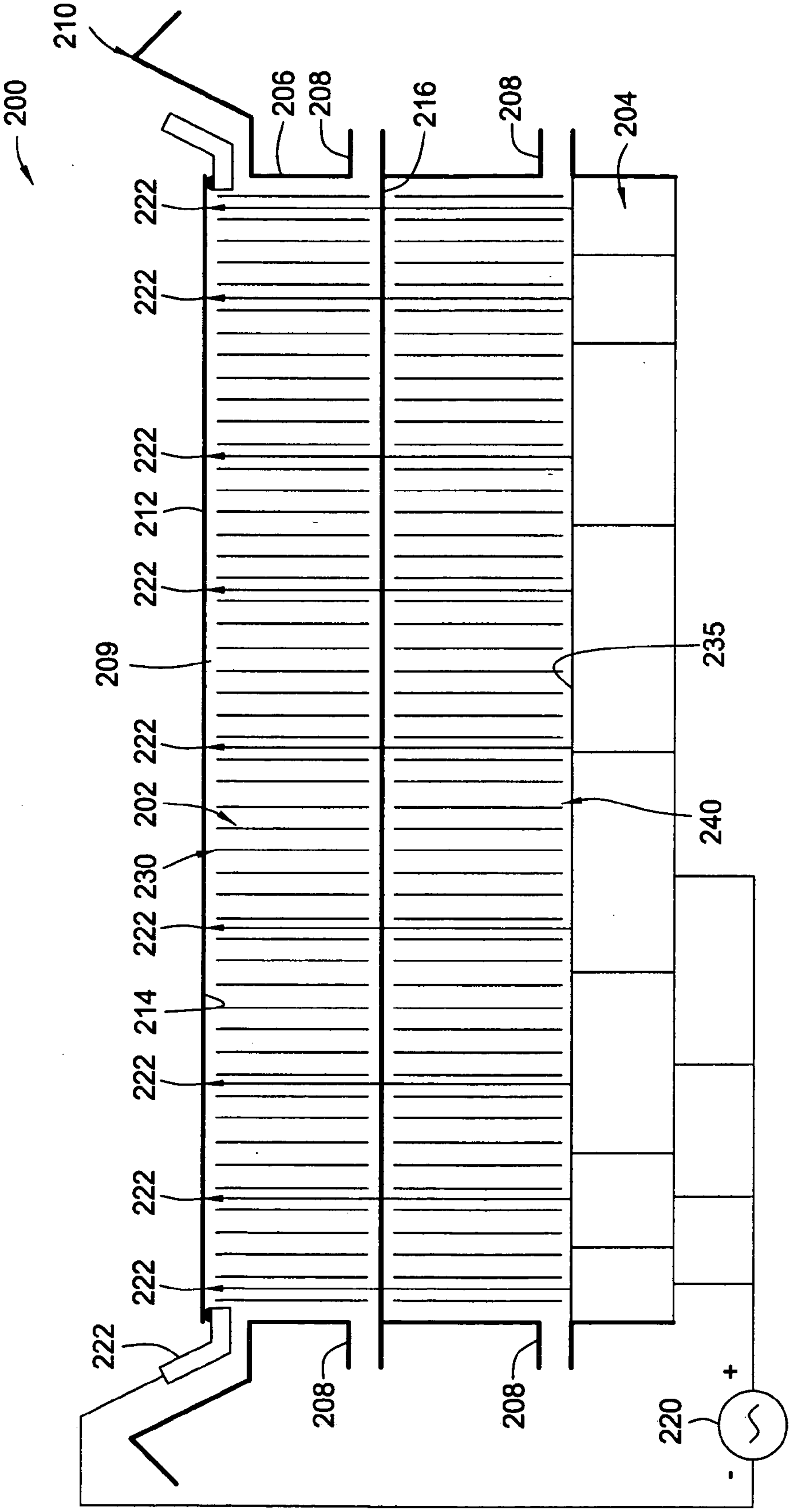


FIG. 1
(PRIOR ART)


200
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212
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FIG. 2

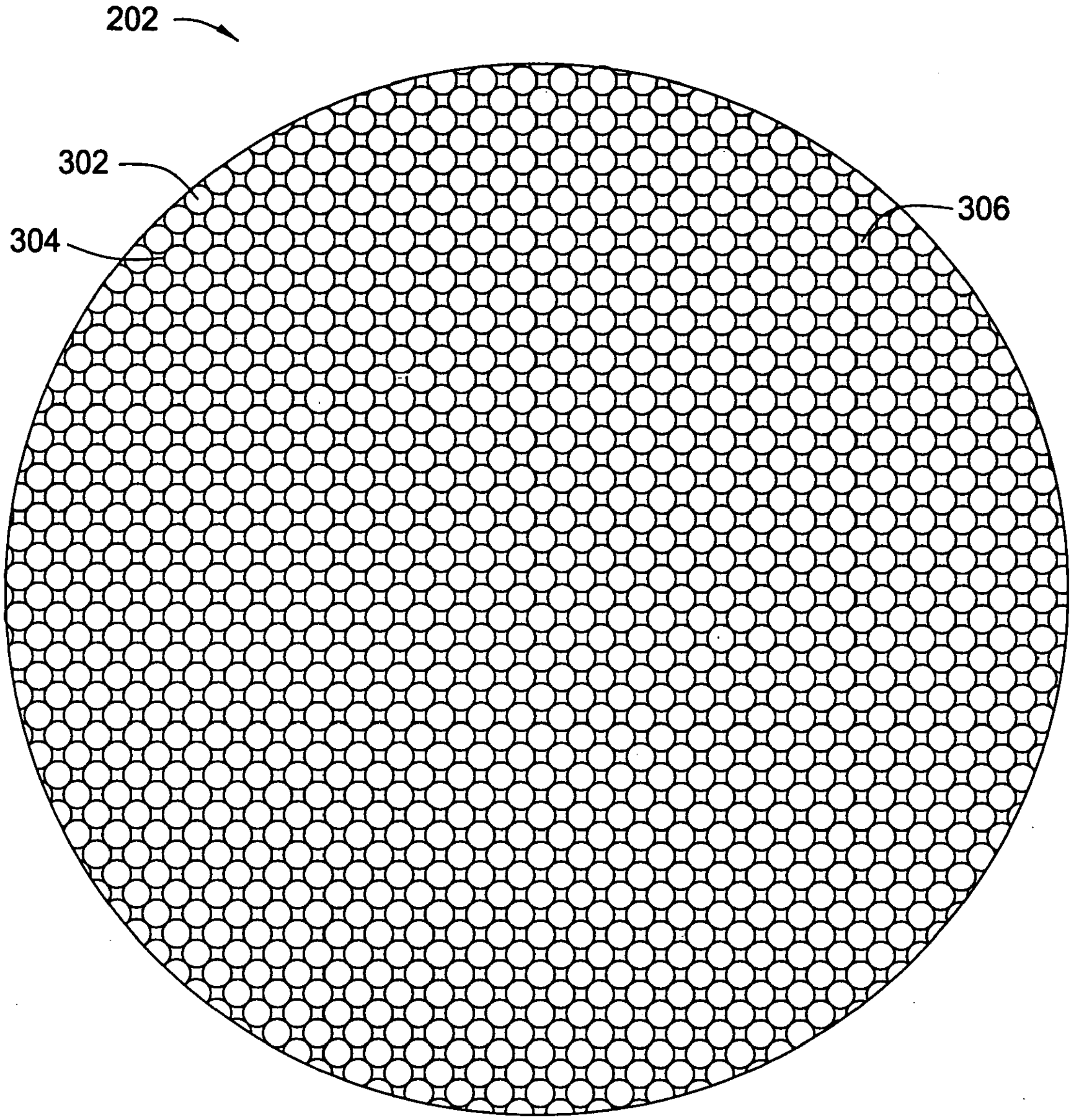

FIG. 3A

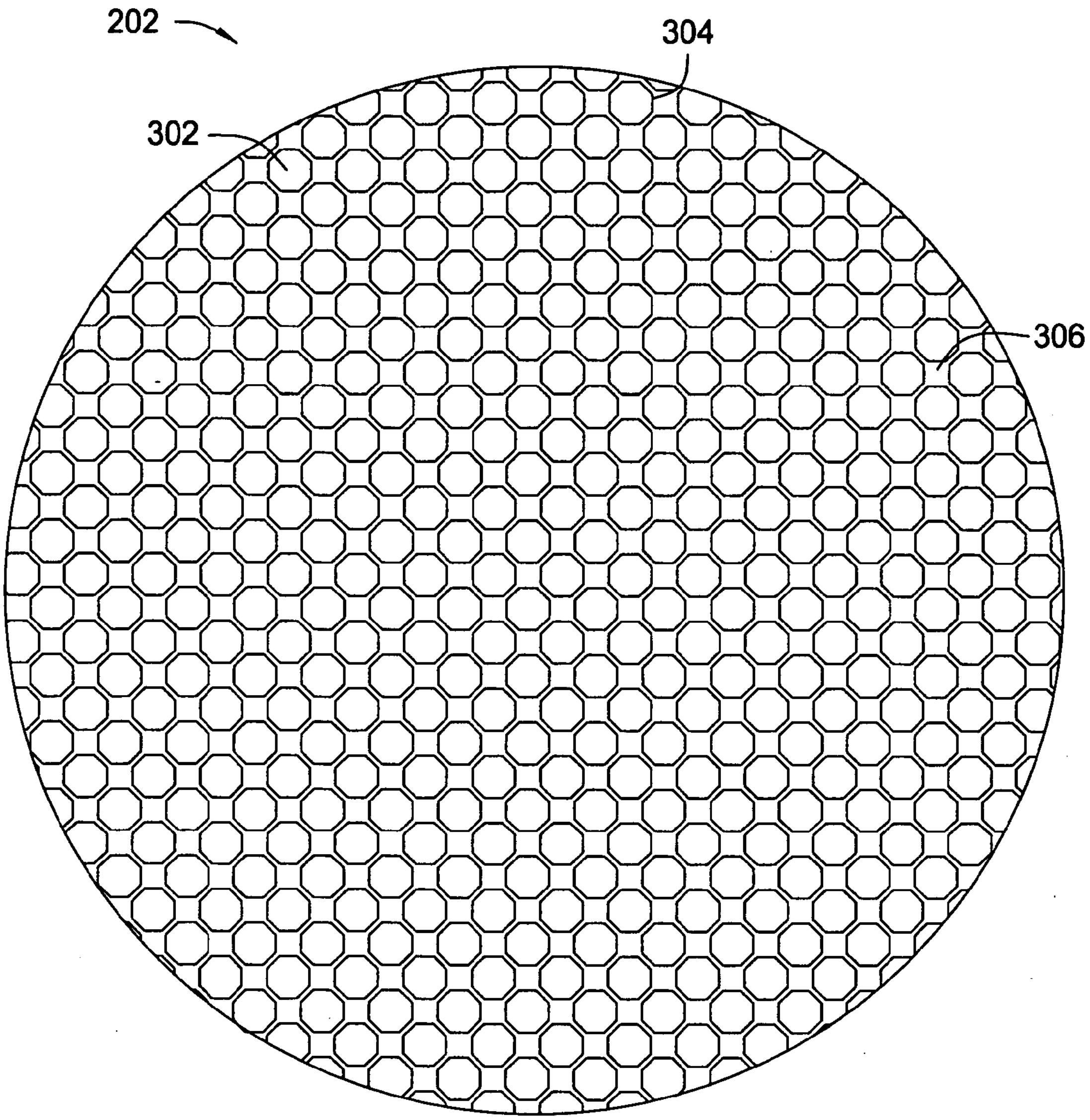

FIG. 3B

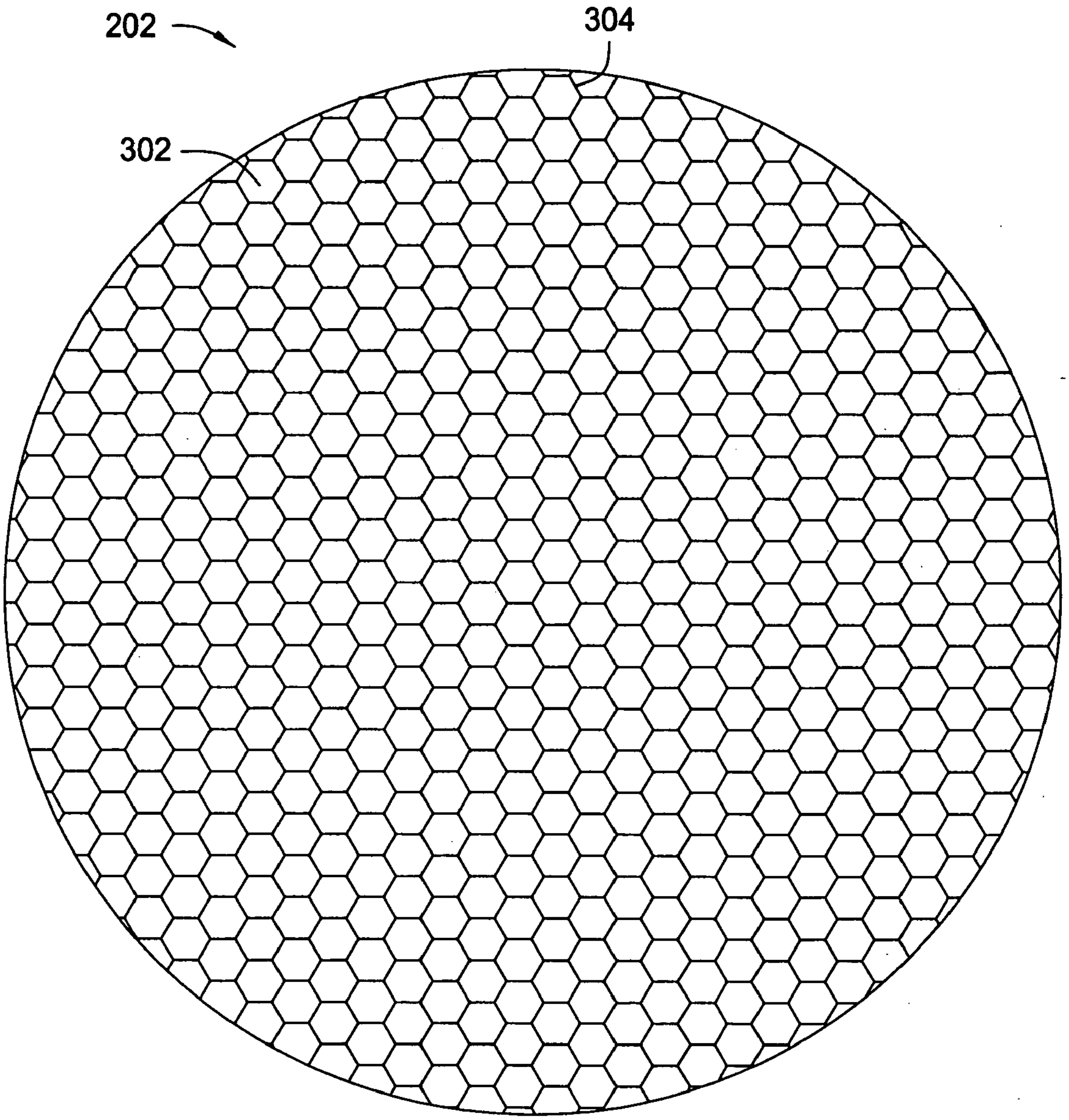

FIG. 3C

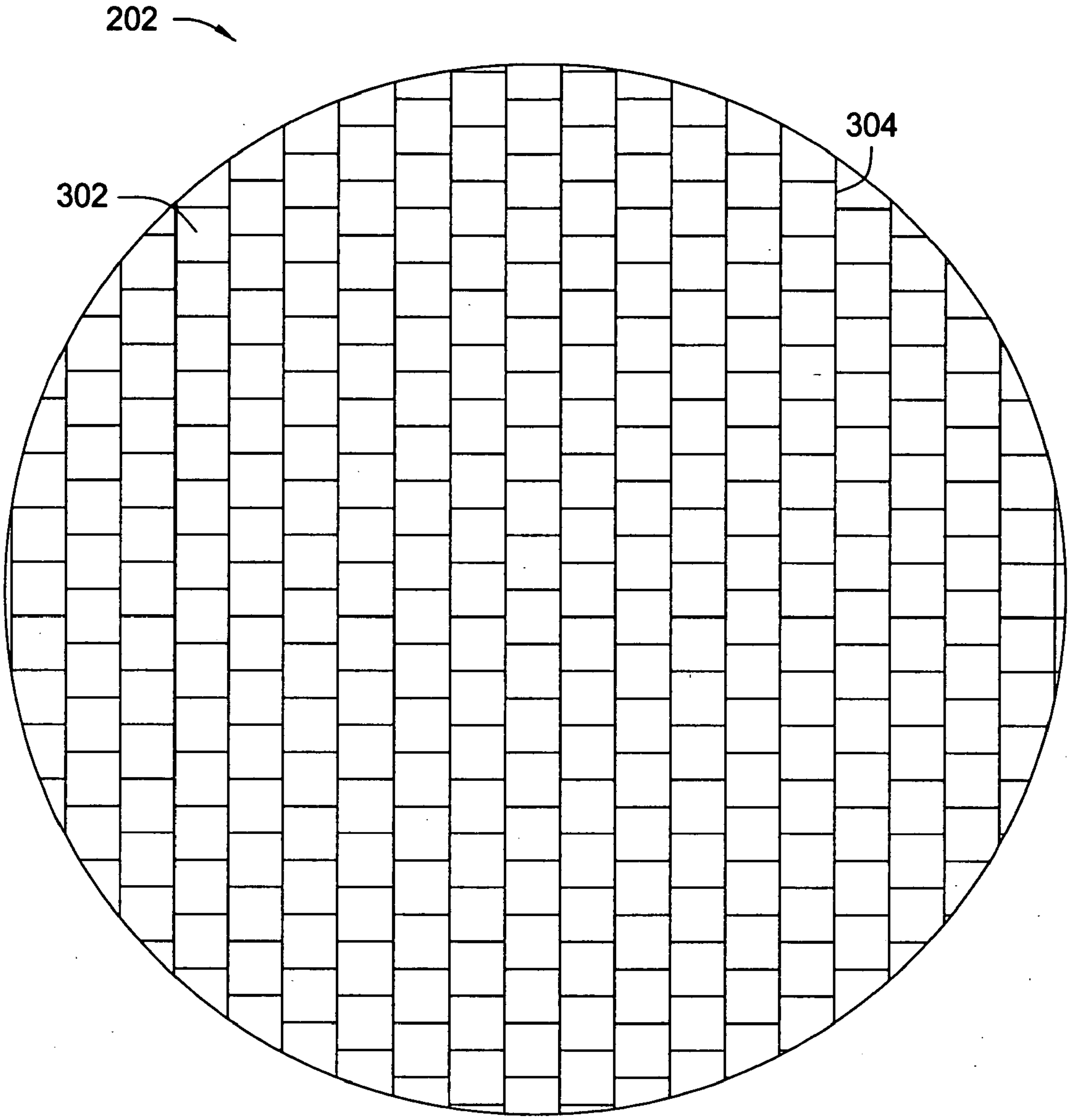

FIG. 3D

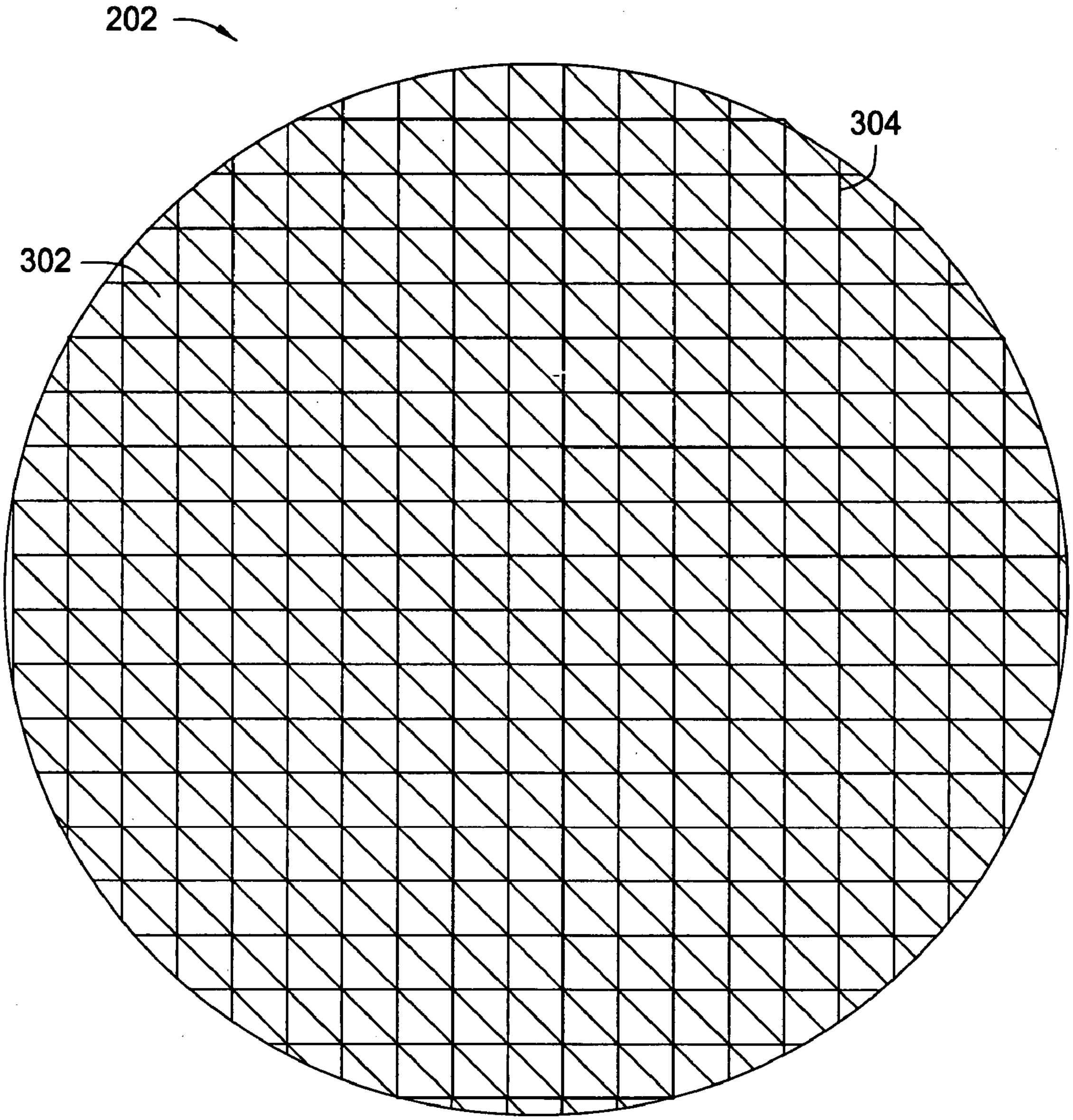

FIG. 3E

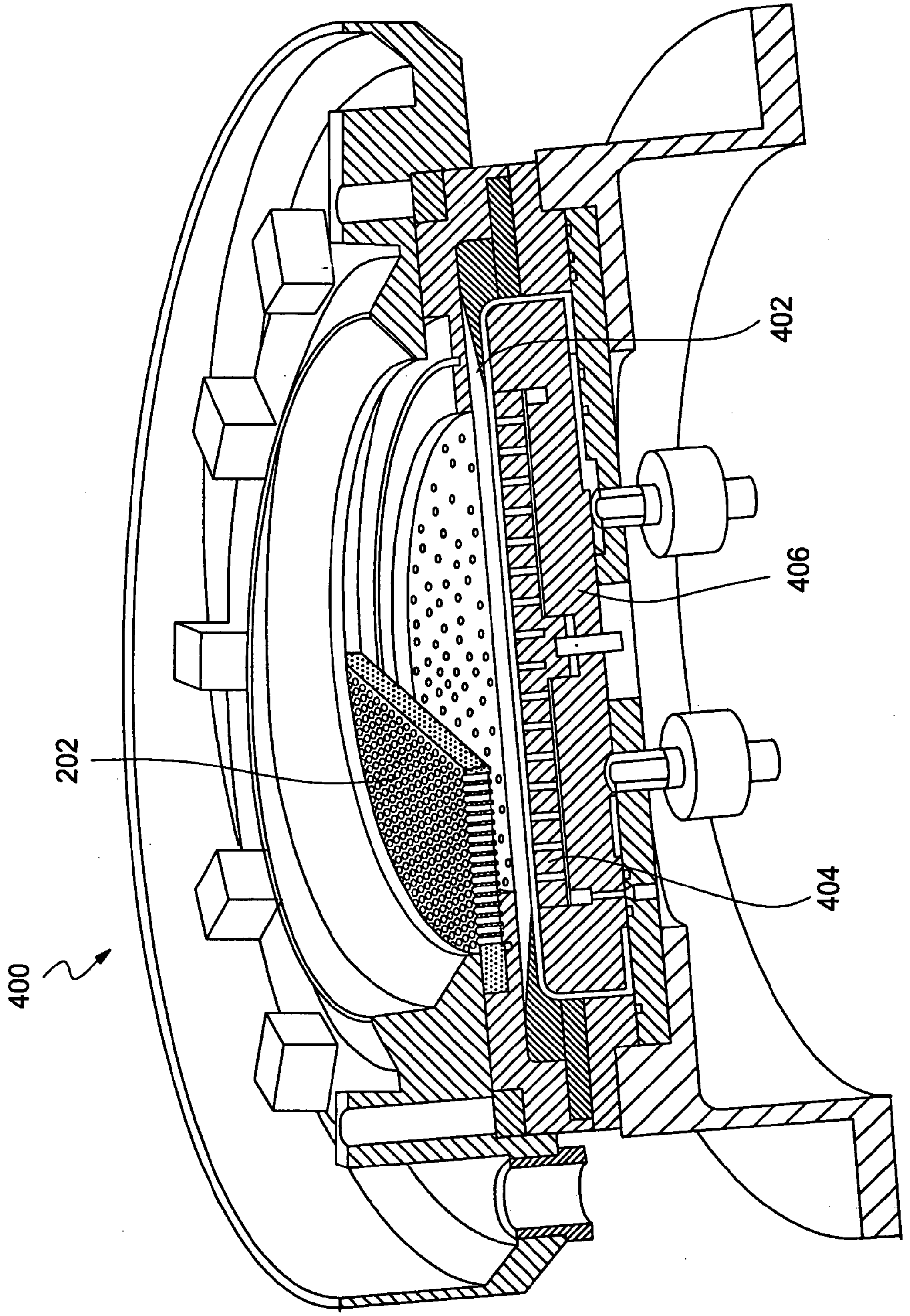

FIG. 4

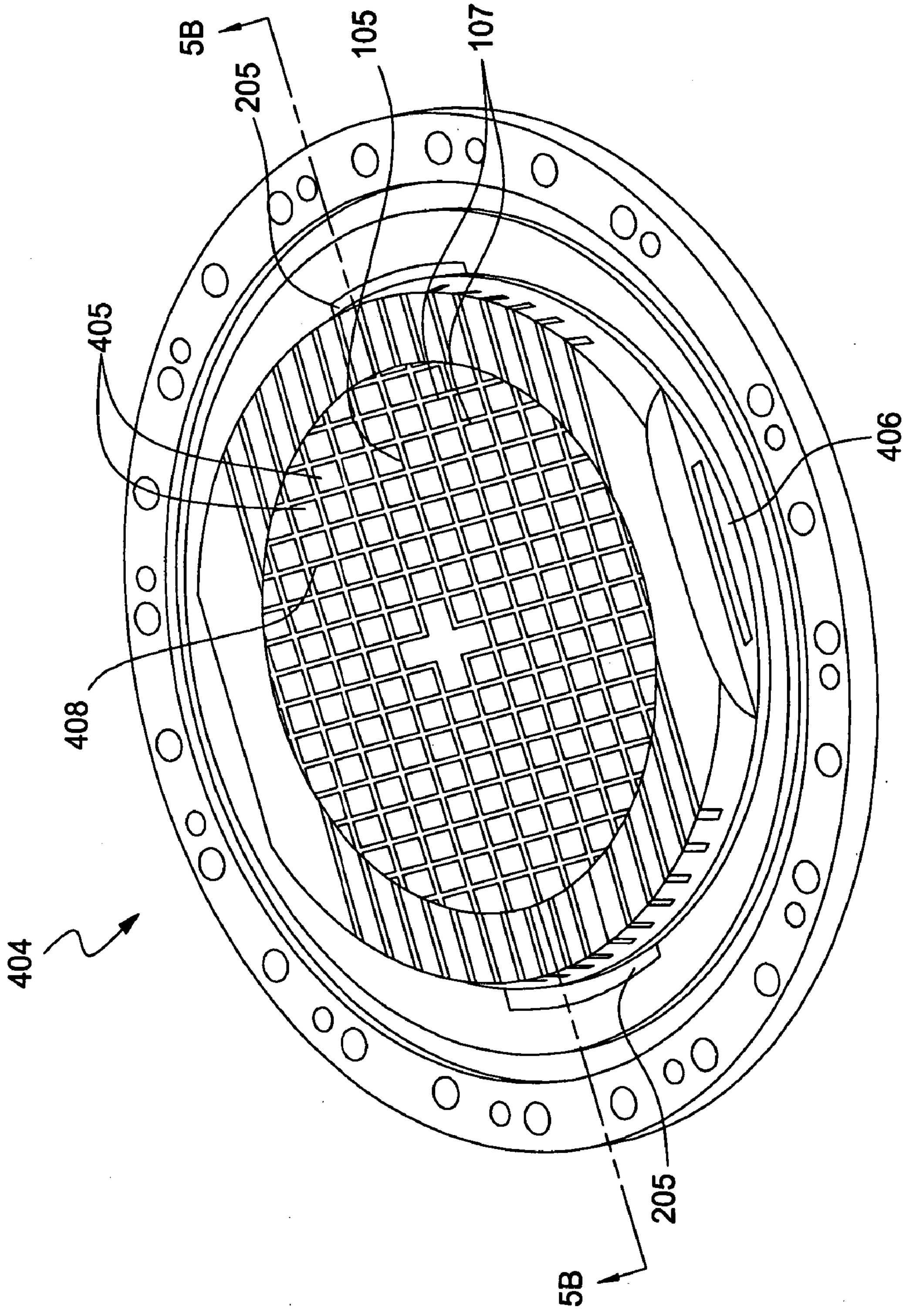

FIG. 5A

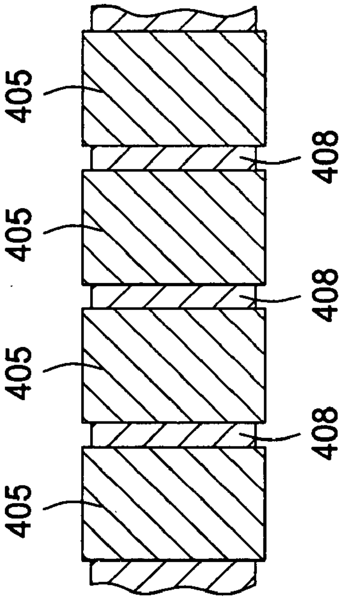
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FIG. 5B

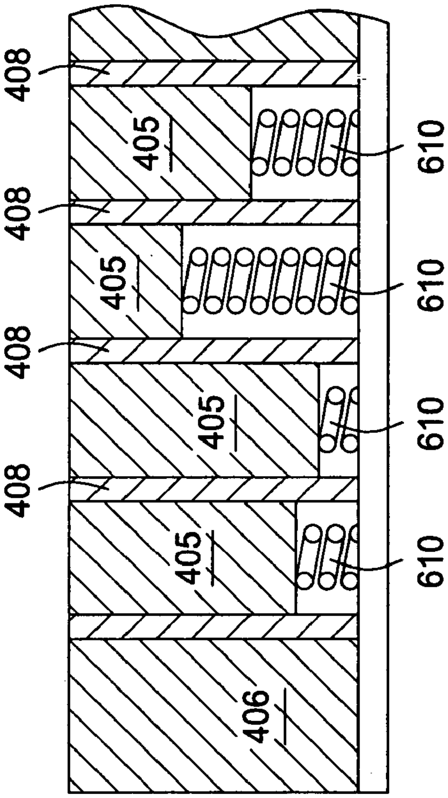
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FIG. 6

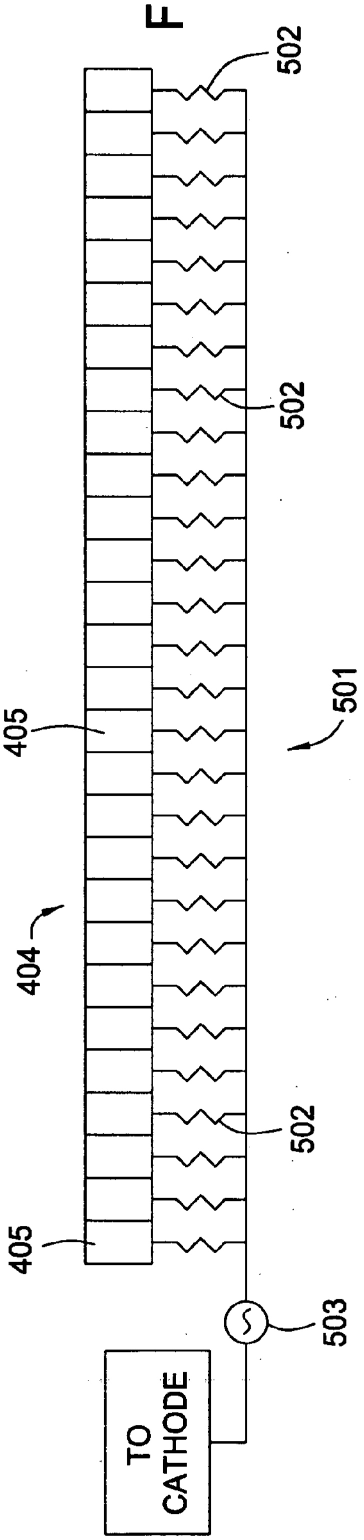

FIG. 5C

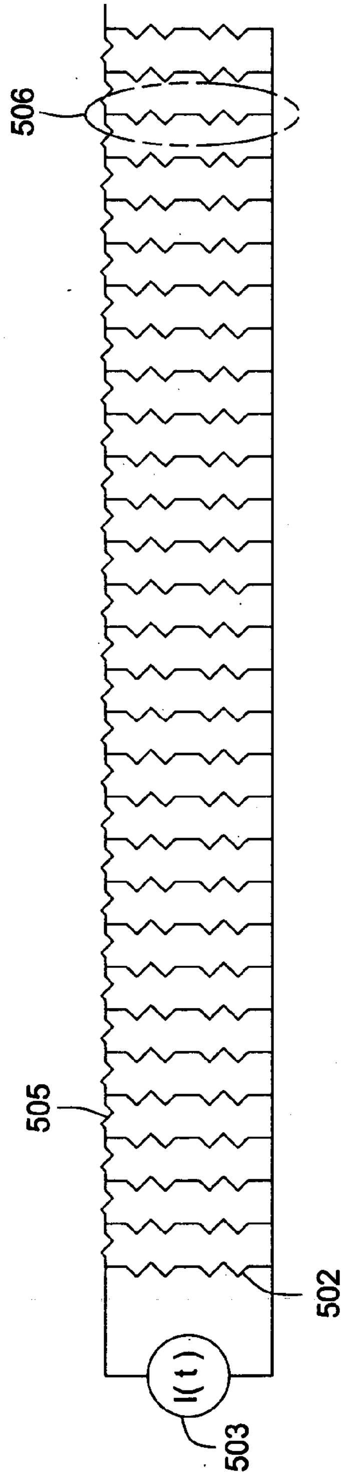

FIG. 5D

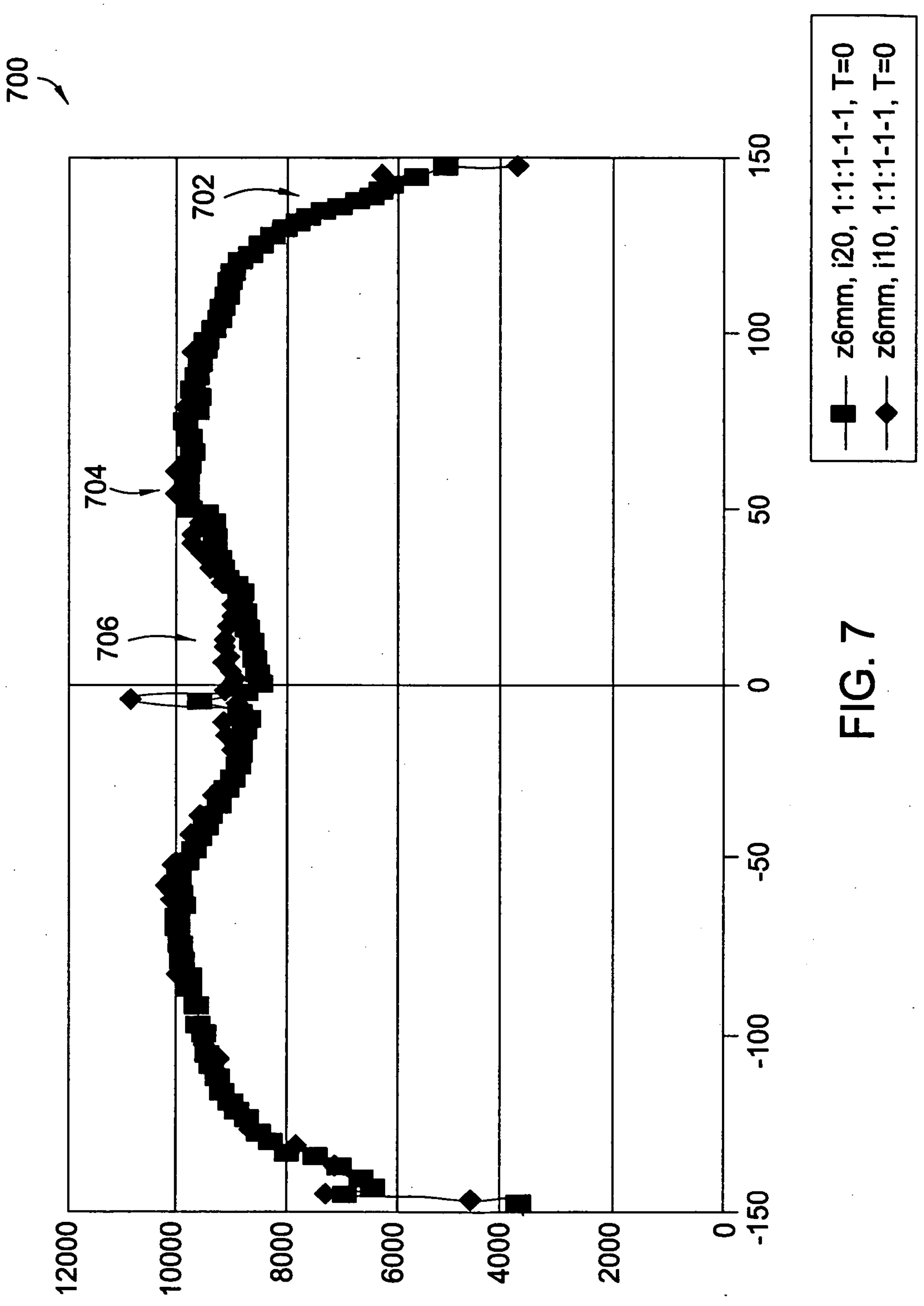
700
702
704
706
12000
10000
8000
6000
4000
2000
0
-150
-100
-50
0
50
100
150
z6mm, i20, 1:1:1-1-1, T=0
z6mm, i10, 1:1:1-1-1, T=0

FIG. 7

CURRENT COLLIMATION FOR THIN SEED AND DIRECT PLATING

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] Embodiments of the invention generally relate to an electrochemical plating cell having an electric field collimator positioned between the anode and the substrate being plated.

[0003] 2. Description of the Related Art

[0004] In semiconductor processing, electrochemical plating (ECP) is generally the preferred technique for filling features formed onto substrates with a conductive material. A typical ECP process generally includes immersing a substrate into an electrolyte solution that is rich in ions of the conductive material (generally copper), and then applying an electrical bias between a conductive seed layer formed on the surface of the substrate and an anode positioned in the electrolyte solution. The application of the electrical bias between the seed layer and the anode facilitates an electrochemical reaction that causes the ions of the conductive material to plate onto the seed layer.

[0005] However, with conventional ECP processes and systems, the conductive seed layer formed on the substrate is generally very thin, and as such, is highly resistive. The resistive characteristics of the seed layer causes the electric field traveling between the anode and the seed layer in a plating process to be much more dense near the perimeter of the substrate where electrical contact with the seed layer is generally made. This increased electric field density near the perimeter of the substrate causes the plating rate near the perimeter of the substrate to increase proportionally. This phenomenon is generally known as the "terminal effect", and is an undesirable characteristic associated with conventional plating systems.

[0006] The terminal effect is of particular concern to semiconductor processing, because as the size of features continues to decrease and aspect ratios continue to increase, the seed layer thickness will inherently continue to decrease. This decrease in the thickness of the seed layer will further heighten the terminal effect, as the decreased thickness of the seed layer further increases the resistivity of the layer.

[0007] Therefore, there is a need for an electrochemical plating cell and method for plating onto semiconductor substrates, wherein the plating cell and method are configured to eliminate the terminal effect.

SUMMARY OF THE INVENTION

[0008] Embodiments of the invention generally provide an electrochemical plating cell having a collimator positioned between the anode of the cell and a substrate positioned in the cell for plating. The collimator operates to channel the electric field traveling from the anode to the substrate, such that the electric field travels in a substantially linear path. The plating cell of the invention further provides for a zoned anode, wherein each of the zones comprises a non-concentrically shaped anode element.

[0009] Embodiments of the invention may further provide a method and apparatus for plating a conductive material onto a substrate. The apparatus includes a fluid processing cell having a fluid basin configured to contain an electrolyte solution and having an opening configured to receive a substrate for processing, an anode assembly positioned in the fluid basin, and a collimator positioned in the fluid basin between the anode and the opening.

[0010] Embodiments of the invention may further provide an electrochemical plating cell having a cell body configured to contain a plating solution therein and having an opening configured to receive a substrate for plating. The cell further includes an anode assembly positioned in the cell body such that the anode assembly is in electrical communication with the plating solution, and an electric field collimator positioned in the cell body between the anode assembly and the opening, the collimator comprising a plurality of electrically insulative fluid conduits having substantially parallel longitudinal axes.

[0011] Embodiments of the invention may further provide a method for plating a conductive material onto a substrate, wherein the method includes generating an electric field between an anode positioned in a plating cell and a substrate being plated in the plating cell, collimating the electric field in a substantially linear direction between the anode and the substrate, and plating the conductive material onto the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of 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.

[0013] **FIG. 1** illustrates a schematic view of a conventional plating cell and the electric field lines generated therein.

[0014] **FIG. 2** illustrates a schematic sectional view of a plating cell of the invention having a collimator positioned therein.

[0015] **FIG. 3A** illustrates a plan view of an exemplary collimator of the invention using circular conduits

[0016] **FIG. 3B** illustrates a plan view of an exemplary collimator of the invention using octagonal conduits.

[0017] **FIG. 3C** illustrates a plan view of an exemplary collimator of the invention using hexagonal conduits.

[0018] **FIG. 3D** illustrates a plan view of an exemplary collimator of the invention using square conduits.

[0019] **FIG. 3E** illustrates a plan view of an exemplary collimator of the invention using triangular conduits.

[0020] **FIG. 4** illustrates a sectional view of an exemplary plating cell of the invention having a collimator in the cell.

[0021] **FIG. 5A** illustrates a top perspective view of an exemplary anode assembly in the plating cell of the invention.

[0022] **FIG. 5B** illustrates a sectional view of the exemplary anode assembly of the plating cell of the invention.

[0023] **FIG. 5C** illustrates a sectional/schematic view of the anode assembly of the invention with schematic representation of the power supply connections to the individual anode members.

[0024] **FIG. 5*d*** illustrates an electrical resistance schematic view of an exemplary plating cell of the invention.

[0025] **FIG. 6** illustrates partial sectional view of the exemplary anode assembly of the invention including an anode adjustment member.

[0026] **FIG. 7** illustrates a plating thickness plot for a plating cell incorporating the collimator of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0027] **FIG. 1** illustrates a schematic view of a conventional plating cell **100** and the electric field lines generated therein. The conventional plating cell **100** generally includes a fluid basin **101** configured to contain a fluid volume **102**, which is generally an electrolyte plating solution. An anode **104** is positioned in a lower portion of the fluid basin **101** and a substrate **106** that is to be plated is generally positioned across an upper open portion of the cell **100**. The substrate **106** is supported by a contact ring that is configured to electrically contact the plating surface **108** of the substrate **106** near the perimeter of the substrate **106** via one or more electric contact elements **110**. The electric contact elements **110** are in electrical communication with a cathodic terminal of a power supply **114**, while the anodic terminal of the power supply is in electrical communication with the anode **104**. Further details of the conventional plating cell **100** may be found in commonly assigned U.S. Pat. No. 6,271,433, which is hereby incorporated by reference in its entirety to the extent not inconsistent with the present invention.

[0028] **FIG. 1** also illustrates the electric field lines **112** generated during a plating process in the conventional plating cell **100**. As noted above, the substrate plating surface **108** has a thin conductive seed layer deposited thereon and the electric field lines **112** inherently converge toward the electrical contact elements **110** as a result of the least resistive path between the anode and the cathode being toward the perimeter of the substrate proximate the contact elements **110**. Several manufacturers of plating cells have attempted to solve the convergence problem by substantially increasing the resistivity of the electrolyte, however, it has been shown that this causes an unacceptable decrease in plating rates and does not sufficiently reduce the electric field convergence effect.

[0029] **FIG. 2** illustrates a schematic sectional view of a fluid processing or plating cell **200** of the invention having a collimator **202** positioned therein. The plating cell **200** generally includes a fluid basin **206** that defines a fluid volume therein and has an open upper portion that is configured to receive a substrate **212** for plating. The basin **206** includes at least one fluid inlet/outlet **208** and an uppermost weir **210** that defines the opening that receives the substrate **212**. The fluid inlets/outlets **208** may be configured to supply plating solutions, e.g., anolyte and/or catholyte solutions, to various regions or volumes within the fluid basin **206**. The electrolyte (anolyte and/or catholyte solutions) supplied to the fluid basin generally overflows the uppermost weir **210**, which is positioned above a processing position of the substrate **212** (so that the substrate plating surface **214** is immersed in the electrolyte contained in the fluid basin **206**).

[0030] The lower portion of basin **206** includes an anode assembly **204**. The anode electrode assembly **204**, which may include several independently powered electrode elements, as will be further discussed herein, in electrical communication with an anodic terminal of a power supply **220**. The cathodic terminal of the power supply **220** is in electrical communication with a substrate contact ring **222** that is configured to support and electrically contact the plating surface **214** of the substrate **212**. Exemplary contact rings may be found in commonly assigned U.S. patent application Ser. No. 10/355,479, filed Jan. 31, 2003, entitled "Contact Ring with Embedded Flexible Contacts", U.S. patent application Ser. No. 10/278,527, filed Oct. 22, 2002, entitled "Plating Uniformity Control by Contact Ring Shaping" and U.S. Pat. No. 6,251,236, all of which are hereby incorporated by reference in their entirety to the extent not inconsistent with the present invention. The plating cell **200** may optionally include a membrane **216**, such as a cationic membrane, for example, positioned across the interior volume of the fluid basin **206** between the anode **204** and the substrate **212**. When membrane **216** is implemented, the fluid basin inlet/outlets **208** may be configured to supply different electrolytes to the volumes above and below the membrane **216**, i.e., a catholyte solution to the volume above the membrane and an anolyte solution to the volume below the membrane, for example. An exemplary plating cell incorporating the membrane separation noted above may be found in commonly assigned U.S. patent application Ser. No. 10/627,336, filed Jul. 24, 2003, entitled "Electrochemical Processing Cell", which is hereby incorporated by reference in its entirety to the extend not inconsistent with the present invention.

[0031] The collimator **202** may be a single unit when no membrane **216** is implemented, or alternatively, when a membrane **216** is implemented, a first collimator may be positioned above the membrane **216** and a second collimator may be positioned below the membrane **216**. Similarly, in embodiments where a membrane **216** is implemented, a single collimator may be positioned above the membrane **216**, however, in this embodiment, it is desirable to have the membrane **216** positioned as close to the anode assembly **204** as possible to prevent electric field divergence (horizontal movement) from the center of the cell prior to the electric field entering the collimator **202**, as will be further discussed herein.

[0032] The collimator **202**, which is illustrated in plan view in **FIG. 3A**, generally includes a plurality of elongated conduits positioned adjacent to each other and having substantially parallel axes. The plurality of conduits **304** are generally manufactured from a dielectric material, such as ceramics, PVDF, plastic materials, Teflon®, or other electrically resistive or insulating materials that are non-reactive with electrochemical plating solutions. Each of the conduits **304** forms an elongated hollow interior region **302** that fluidly communicates one terminating end of the conduit **304** with an opposing terminating end of the conduit. The plurality of conduits **304** are affixed together such that the longitudinal axis of each of the conduits is generally parallel to each of the other axes of the conduits **304**, and further, the axes of the conduits **304** are generally positioned orthogonal to the plating surface **214** of the substrate **212** being plated in the plating cell **200**. As such, the longitudinal axes of conduits **304** are generally positioned orthogonal to both the upper surface of the anode assembly **204** and to the substrate plating surface **214**. The conduits **304** may be affixed together via glue or epoxy process, via a heat treatment process, a sintering process, or other process suitable to affix the conduits **304** together such that the assembled collimator **202** is rigid and capable of supporting its own weight without substantial deflection or bowing.

[**0033**] Assembly of the collimator **202** in a manner that prevents substantial deflection or bowing in a plating process is important to the operation of the invention. More particularly, as noted herein, the upper surface **230** of the collimator **202** is preferably positioned between about 0.5 mm and about 20 mm, or more particularly, between about 1 mm and about 10 mm, or about 15 mm away from the plating surface **214** of the substrate **212**. This spacing operates to prevent excessive lateral or horizontal divergence of the electric field exiting from the conduits **304** before the electric field contacts the plating surface **214**. If the collimator **202** is manufactured in a manner that allows for bowing or vertical deflection, then the spacing between the collimator **202** and the plating surface **214** will be increased near the middle of the plating cell, and as a result thereof, horizontal or lateral movement of the electric filed will be more likely near the center of the cell as a result of the increased spacing. Allowing the electric field to diverge away from the center of the cell furthers the terminal effect, and as such, is undesirable in the present invention. Thus, vertical rigidity of the collimator **202**, i.e., the ability to retain shape/remain planar under its own weight, and additionally, under processing conditions that include fluid flow, is an important aspect of the invention.

[**0034**] Further, the conduits **304** are generally affixed together in a manner such that the space **306** between the outer surfaces of the conduits **304** may also form a conduit from one side of the collimator **202** to the other side thereof. The space **306** shares a parallel axis with the other conduits **304**, and as such, further facilitates the electric field channeling of the invention. In other embodiments of the invention, the collimator **202** may be manufactured from various shapes of conduits **304** that may or may not form space **306**. For example, conduits **304** may be triangular, square, pentagonal, hexagonal, heptagonal, octagonal, nonagons, decagons, or other polygon shapes. For example, **FIG. 3B** illustrates a plan view of a collimator **202** of the invention manufactured from octagonal conduits; **FIG. 3C** illustrates a plan view of a collimator **202** of the invention manufactured from hexagonal conduits; **FIG. 3D** illustrates a plan view of a collimator **202** of the invention manufactured from square conduits; and **FIG. 3E** illustrates a plan view of an exemplary collimator of the invention using triangular shaped conduits.

[**0035**] Additionally, other embodiments of the invention contemplate that the collimator **202** may be formed by boring conduits of varying cross sectional shapes out of a solid disk of material. For example, a plurality of circular or other polygon shaped bores may be formed into a solid disk of material to generate a collimator **202**.

[**0036**] **FIGS. 3C, 3D**, and 3E include polygon shaped conduits **302** that do not generate any vertical space **306** between the respective conduits, i.e., these embodiments eliminate the space **306** illustrated in **FIGS. 3A and 3B** by having the respective conduits abut directly against each other, and therefore, these embodiments of collimator **202** do not include the additional conduits formed by the spaces **306**. As such, these embodiments of the collimator **202** provide conduits that are all symmetric and identically shaped, which may operate to provide a more uniform electric field at the substrate surface during plating operations as a result of the elimination of the spaces **306** that are not shaped identically to the shape of the conduits **302**.

[**0037**] Collimator **202** is generally positioned such that an upper terminating surface **230** of the collimator **202** is positioned proximate to and in a generally parallel relationship with the plating surface **214**, and such that a lower terminating surface **240** is positioned proximate to and generally parallel to an upper surface **235** of the anode assembly **204**. The positioning of the upper and lower surfaces **230, 240** proximate the plating surface **214** and the upper surface **235** of the anode assembly **204** operates to restrict horizontal flow or dispersion of the electric field traveling from the anode **204** to the plating surface **214**. The spacing of the lower surface **240** may be generally the same as the upper surface, e.g., the spacing between the anode **204** and the lower surface **204** may be as recited herein with respect to the spacing between the plating surface **214** and the upper surface **230**. Arrows **222** in **FIG. 2** illustrate the electric field flow in a plating cell **200** of the invention incorporating the collimator **202**. The electric field flow **222** is substantially vertical and has minimal horizontal movement or dispersion, as the conduits of the collimator **202** prevent the electric field from traveling horizontally or dispersing while traveling therethrough. During the time period when the electric field is entering and exiting the collimator **202**, e.g., when the electric field is traveling from the anode assembly **204** to the collimator **202** and when the electric field is traveling from the collimator **202** to the plating surface **214**, the electric field is not prevented from dispersing. As such, it is desirable to minimize the vertical distance **208** between the collimator and the plating surface **214** and between the collimator **202** and the anode assembly **204**, as these distances directly impact the dispersion ability of the electric field.

[**0038**] More particularly, in order to minimize horizontal electric field movement in the plating cell of the invention, the upper and lower terminating ends **230, 240** are positioned proximate the plating surface **214** and the upper surface **235** of the anode **204**, respectively. More particularly, the inventors have found that when the upper terminating end **230** of the collimator **202** is positioned less than about 15 mm from the plating surface **214**, and more particularly, within about 7 mm, or within about 3 mm from the plating surface **214**, that horizontal electric field movement is essentially eliminated, i.e., the only area where the electric field can travel horizontally is in the space **209** between the upper terminating end **230** of the collimator **202** and the plating surface **214**. Since the space **209** is very small as a result of the spacing between the collimator **202** and the substrate being in the range of about a 0.5 mm to about a 5 mm gap, there is little area for the electric field to travel or disperse horizontally. Further, although the inventors have determined that the closer the upper terminating end **230** of the collimator **202** is to the plating surface, the greater the reduction in the horizontal electric field movement, embodiments of the invention are not limited to configurations where the collimator **202** is positioned less than about 15 mm from the plating surface **214**. Different processing conditions and plating requirements may allow for placement of the collimator **202** farther from the plating surface **214**, e.g., between about 5 mm and about 25 mm away, for example, while still maintaining acceptable processing results for particular processing applications.

[**0039**] Similarly, the positioning of the lower surface **240** of the collimator **202** close to the membrane **402** also operates to minimize horizontal electric field movement. For example, in the plating cell of the invention, membrane **402** operates to transmit the electric field emitted from the anode **204** therethrough so that the electric field can travel to the substrate to facilitate the electrochemical plating process. Positioning the lower surface **240** of the collimator **202** within about 15 mm from the membrane **402** operates to capture the electric field being traveling through the membrane **402** before the electric field is able to travel horizontally. Once the electric field is captured by the conduits of the collimator **202**, the electric field is vertically channeled toward the substrate plating surface. Positioning the collimator **202** closer, i.e., within about 10 mm, for example, from the anode **204** further assists with minimizing electric field divergence in the plating cell of the invention.

[**0040**] Another factor that impacts the ability of the invention to prevent horizontal dispersion of the electric field is the size, and in particular, the cross sectional width or diameter of the conduits **302**. More particularly, when circular conduits **302** are implemented, for example, it is desirable to have the cross sectional diameter of each of the conduits **302** to be less than about 10 mm, and more particularly, between about 2 mm and about 10 mm, or between about 1 mm and about 5 mm, for example. Smaller diameters of conduits **302**, i.e., less than about 10 mm, have been experimentally shown to provide improved electric field collimation and reduced electric field dispersion over larger diameter conduits **302**, i.e., greater than about 15 mm for semiconductor processing. In embodiments of the invention where measurements of diameter are inapplicable, i.e., where some polygon or triangular shapes are implemented, then the cross sectional area of the conduit **302** should be minimized. For example, it is desirable to have the cross sectional area of the conduits to be between about 2 mm^2 and about 30 mm^2. Additionally, for a 300 mm substrate processing cell, for example, there will generally be more than about 250 of the fluid conduits **302** that are used to form the collimator **202**. In embodiments where the inner diameter of the conduits **302** is smaller and the conduits **302** are closely packed, the number of conduits used for a 300 mm plating cell may be more than about 500, or more than about 1000, for example.

[**0041**] In another embodiment of the invention, the terminating ends of the conduits **302** may increase or decrease in diameter. For example, the lower end of the conduits, i.e., the end proximate the anode, may be funnel shaped in order to gather the electric field. Both the upper and lower ends may be sized in accordance with the plating characteristics desired. In this embodiment of the invention, the upper and lower portions of the conduits may be larger or smaller than the respective other end.

[**0042**] In another embodiment of the invention, the collimator **202** is sized and positioned such that the vertical size or height of the collimator **202** occupies between about 50% and about 99% of the vertical space between the anode **204** and the substrate **212** being plated. More particularly, embodiments of the invention contemplate that the collimator **202** will occupy between about 75% and about 95% of the vertical space between the anode **204** and the substrate **212**, or between about 80% and about 99% of the space between the anode and the substrate being plated. These proportions of occupied space have been shown to substantially reduce terminal effect plating.

[**0043**] **FIG. 4** illustrates a sectional view of an exemplary plating cell **400** of the invention having a collimator **202** in the cell **400**. A general description of the components of plating cell **400** may be found in commonly assigned U.S. patent application Ser. No. 10/268,284, filed Oct. 9, 2002, entitled "Electrochemical Processing Cell", which is hereby incorporated by reference in its entirety to the extent not inconsistent with the present invention. Plating cell **400** generally includes a catholyte volume and an anolyte volume, where the catholyte volume is generally defined as the fluid volume in the plating cell **400** that is above the ionic membrane **402**, and where the anolyte volume is generally defined as the fluid volume in the plating cell **400** that is below the membrane **402** adjacent the anode assembly **404** positioned in the anode base member **406**. However, plating cell **400** differs from the application cited above in that plating cell **400** does not include a diffusion member (illustrated as element **210** in the commonly assigned application). Rather, the diffusion member of the incorporated case is replaced in the present invention with the collimator **202**, as described above.

[**0044**] Collimator **202** is generally positioned above the membrane **402** and below the substrate being plated in the catholyte volume (the fluid volume above the membrane **402**) of the plating cell **400**, i.e., between the substrate being plated and the membrane **402**. The lower surface of the collimator **202** is generally positioned between about 0.1 mm and about 10 mm from the upper surface of the membrane **402**. Preferably, the lower surface of the collimator **202** is positioned between about 0.1 mm and about 5 mm from the upper surface of the membrane **402**, so that the electric field traveling from the anode toward the substrate being plated does not have sufficient vertical space to disperse horizontally or radially outward toward the perimeter or outer wall of the plating cell. Similarly, as discussed above, the upper surface of the collimator **202** is generally positioned as close as possible to the plating surface of a substrate positioned in the cell for plating. More particularly, the upper surface of the collimator **202** may be positioned between about 0.5 mm and about 10 mm, or between about 0.5 mm and about 5 mm from the plating surface of the substrate. This narrow spacing prevents the electric field exiting from the collimator **202** from traveling horizontally (dispersing) toward the edge of the substrate before contacting the plating surface of the substrate, i.e., prevents the electric field effects that are known to cause the terminal effect. Research has shown that placement of the collimator **202** within about 2 mm and about 10 mm from the plating surface is sufficient to substantially eliminate the terminal effect in semiconductor plating processes.

[**0045**] **FIG. 5A** illustrates a top perspective view of an exemplary anode assembly **404** of the plating cell **400** of the invention. The anode assembly **404**, as noted above, is positioned in an anode base assembly **406** and is configured to work with the collimator **202** to control electric field density in the plating cell. The anode base assembly **406** is generally manufactured from an electrically insulative material that is not reactive with electrochemical plating solutions. Further details of the construction and operation of the anode base assembly **406** and surrounding components may be found in commonly assigned U.S. patent application Ser. No. 10/627,336, filed Jul. 24, 2003, entitled "Electrochemical Processing Cell", which is incorporated by reference in its entirety to the extent not inconsistent with the present invention.

[0046] The anode assembly **404** of the invention generally includes a plurality of individual anode members **405** that cooperatively form the anode assembly **404**. For example, embodiments of the invention may include between about 20 and about 200 individual anode members **405** that collectively form the anode assembly **404**. The individual anode members **405** may be manufactured from a soluble conductive material, such as copper for a copper electrochemical plating system, or from another material that is soluble in an electrochemical plating solution. Alternatively, the individual anode members **405** may be manufactured from an insoluble conductive material, such as platinum, titanium, or other insoluble metals amenable to electrochemical plating solutions. Further, the conductive material of anode members **405** may be coated with another conductive material, such as platinum, for example. The individual anode members **405** may be manufactured as square shaped (in plan view) conductive members, wherein an electrically insulative spacer **408** may be positioned between the respective square shaped anode members **405** to electrically isolate the anode members **405** from each other, as illustrated in the sectional view of the anode member in **FIG. 5B**. The spacers **408** generally have a thickness of less than about 3 mm, and more particularly, less than about 1 mm, so that the surface area on the anode surface that is not electrically active is minimized, as inactive surface area on the anode has been shown to facilitate plating uniformity problems, such as the problems associated with concentric anode configurations where there is a small non-active space between the concentric rings of the anode member. The spacers **408** used in the present anode assembly **404** may be made from any insulative or dielectric material that is not reactive with electrochemical plating solutions, such as, PVDF, Teflon®-type materials, plastics, insulative oxides, anodized materials, the same material as the anode, etc. Additionally, the central portion of the anode assembly **404** may include a collection of anode members **405** that do not have insulative spacers **408** positioned therebetween, as the inventors have found that the spacers tend to create low plating areas on the substrate when positioned proximate the center of the anode assembly **404**.

[0047] The upper surface of each of the respective anode members **405** are generally positioned in a substantially parallel orientation with each other such that a unitary planar upper anode surface is generated. Further, each of the respective anode members **405** is also generally in electrical communication with an anodic terminal of a power supply (as illustrated in **FIG. 2**). The electrical power or current applied to each of the respective anode members **405** may be individually controlled or regulated by a controller (not shown). The controller may be used to adjust the resistance of a variable resistor (not shown), for example, positioned in series electrical connection between each individual anode member **405** and the power supply. The controller may be a microprocessor type controller configured to control a processing sequence, as is generally known in the art. The controller may be modified, however, to allow for control of the individual anode members **405**. The anode members **405** may further be controlled in groups or banks, e.g., regions of the anode assembly **404**, such as a group of anode members **405** in the central portion of the anode assembly **404** and a surrounding group of anode members **405** near the perimeter of the anode assembly **404**. The controlled banks or groups of anode members **405** may be in any shape, size, or number. For example, concentric or symmetrically shaped regions or banks may be used. In one embodiment of the invention, the anode assembly **404** is divided into at least two concentric regions, wherein a first region covers the center of the anode assembly **404** and at least one second region covers an annularly shaped region surrounding the center region. In this embodiment, the center region may be powered to generate a greater plating rate near the center of the substrate, which further minimizes the terminal effect.

[0048] **FIG. 5C** illustrates a sectional/schematic view of the anode assembly **404** of the invention with schematic representation of the power supply connections to the individual anode members **405**. In this embodiment, each of the respective anode members **405** is in series electrical connection with a variable resistor **502**. The plurality of variable resistors **502** (one resistor **502** for each anode member **405**) are in parallel electrical connection with each other. The parallel relationship of variable resistors **502** is in series electrical communication with an anodic terminal of a power supply **503**. The variable resistors **502** are generally controllable by a system controller configured to control the operation of the plating system of the invention. One advantage of this configuration is that only one power supply is needed to drive a plurality of anode members **405**. For an anode member **405** that is square and has a side length of 10 mm, for example, a typical resistance value for the variable resistor is about 10 kΩ.

[0049] **FIG. 5*d*** illustrates an electrical resistance schematic view of the plating cell of the invention. The power supply **503** is in parallel connection with each of the anode member circuits **506**, as illustrated by the dashed line. Each anode member circuit **506** includes the variable resistor **502**, resistance **506** (which represents the resistance of the anode member **405** and the electrolyte solution between the anode member **405** and the substrate being plated), and a horizontal resistance **505** that represents the resistance of the seed layer on the substrate. As noted above, typical resistance values for the 10 mm wide anode members **405** are 10 kΩ, and around 10 ohms for the seed resistors **505**. However, note that the drawing does not illustrate a horizontal resistance for the electrolyte, as this resistance is in parallel with the seed resistance **505**, and generally has a value of between about 5 and 10Ω when the anode members **405** are spaced from the substrate at a distance of about 2 mm. As such, the resistance for the electrolyte may be combined with resistance **505** or generally ignored.

[0050] By having the impedance of the variable resistor **502** be about 1000 times greater than the seed layer resistance **505**, the anode resistors predominate in controlling the current distribution across the surface of the substrate being plated. Thus, as the copper thickness increases during plating, the seed layer resistance will decrease in value, and the anode resistors become more dominant in controlling the current distribution. In the present embodiment of the invention, the value of the variable resistors **502** will generally be inversely proportional to the top surface area of the corresponding anode member **405**. For example, for the previously noted resistance value about 10 kΩ, the top surface area of the anode member **405** would be around 1 cm^2. In this configuration, the current passing through the resistors **502** would be substantial, and as such, the resistors **502** would inherently become heated. As such, the inventors contemplate that cooling (air, fluid, etc.) of the circuits **506** may be required.

[0051] **FIG. 6** illustrates a partial sectional view of the exemplary anode assembly of the invention including an anode adjustment mechanism **610**. The anode adjustment mechanism **610** is positioned below each of the respective anode segments **405** and above the anode base **406**. The anode adjustment member **610** generally includes a mechanism that is configured to vertically move the anode segment **405** positioned thereon. The movement of the anode segment by the adjustment member **610** is calculated to maintain the upper surface of the anode assembly **204** in a substantially planar orientation with respect to the upper surface of the other anode segments **405**. The adjustment member **610** may be configured to vertically move the associated anode segment **405** vertically in response to the changing weight of the anode segment **405**, such as through a weight responsive spring mechanism that will raise the anode segment **405** in proportion to the quantity of material eroded from the segment. This particular embodiment of the invention is configured for use in plating systems incorporating soluble anodes, as soluble anodes are known to erode at varying rates, thus generating a non-planar upper anode surface. Use of the adjustment member **610** allows for individual vertical adjustment of the respective anode segments **405** such that the upper surfaces of the anode segments **405** continually remain coplanar, despite the varying erosion rates of the respective anode elements **405**.

[0052] In operation, embodiments of the invention may be used to plate a conductive material onto a semiconductor substrate in a substantially uniform manner, i.e., substantially eliminating increased plating accumulation near the perimeter of the substrate as a result of the electrical contact being made near the perimeter of the substrate, e.g., the terminal effect. A plating process using embodiments of the invention generally begins with a substrate to be plated being immersed into a plating solution contained in a plating cell of the invention, such as plating cell **200** or **400** illustrated in **FIGS. 2 and 4** respectively. The substrate may be electrically biased during the immersion process to prevent etching of any conductive material already deposited on the substrate prior to initiation of the plating process. Once immersed, the substrate may be positioned in a plating position, i.e., generally an orientation where the plating surface **214** of the substrate is positioned substantially parallel to an anode assembly **204** of the plating cell, as generally illustrated in **FIG. 2**.

[0053] Once the substrate is in the plating position, an electrical plating bias is applied between the anode assembly **204** (connected to an anodic terminal of the power supply) and the substrate plating surface **214** (connected to a cathodic terminal of the power supply) to drive the electrolytic reaction that causes copper ions in the plating solution to deposit onto the plating surface **214**. The plating bias may be a constant current, constant voltage, a pulsed current or voltage, a ramped current or voltage, and may include reverse current or voltage step(s) and/or relaxation intervals between application of plating or deplating electrical bias steps. A more detailed description of the application of the plating bias may be found in commonly assigned U.S. Pat. No. 6,261,433, which is hereby incorporated by reference in its entirety, to the extent not inconsistent with the present invention.

[0054] The application of the plating bias generates a current flow between the anode **204** and the plating surface **214**. The current flow inherently generates an electric field between the anode **204** and the plating surface. This electric field in a conventional plating cell, as shown in **FIG. 2**, tends to diverge toward the perimeter of the substrate where the electrical contact is generally made. This divergence of the electric field causes the deposition rate near the perimeter of the substrate to be greater than the deposition rate near the center of the substrate, as the electric field flux is known to be proportional to the deposition rate.

[0055] The present invention solves the challenges associated with diverging electric field in electrochemical plating cells by positioning the collimator **202** between the anode **204** and the plating surface **214**. The electric field **222** is received by the lower surface of the collimator **202** just above the anode **204**. The electric field **222** is then transmitted via the conduits **302** (shown in **FIG. 3**) of the collimator **202** toward the substrate plating surface **214**. The conduits **302** channel the electric field **222** such that the electric field travels directly toward the plating surface **214**, i.e., in a vertical direction, without horizontal divergence. The electric field is then emitted from the upper surface **230** of the collimator **202** proximate the substrate plating surface **214**. More particularly, the upper surface **230** is generally. positioned less than about 20 mm from the plating surface, and as such, when the electric field is emitted from the conduits **302** of the collimator **202**, the field has minimal opportunity to travel horizontally prior to intersecting with the plating surface. Since the inventors have found that the vertical spacing between the upper surface **230** and the plating surface **214** is controlling of the divergence (smaller spacing between the upper surface **230** and the plating surface **214** provides proportional reduction in horizontal field divergence), embodiments of the invention contemplate that the spacing between the upper surface **230** and the plating surface **214** may be less than about 25 mm, and more particularly, between about 0.5 mm and about 15 mm, as these spacing dimensions provide minimal vertical spacing for horizontal field dispersion.

[0056] **FIG. 7** illustrates a plating thickness plot **700** for a plating cell incorporating the collimator of the invention. The plot was obtained in a plating cell having a plurality of anodes with the collimator positioned less than about 10 mm away from the plating surface of the substrate. The anodes were independently powered with the center anodes receiving more power than the surrounding anodes, and the outer anodes receiving more power than either of the inner anodes. The substrate plated had a diameter of 300 mm and had a 1000 Å thick seed layer formed thereon. A total of 7000 Å was plated onto the seed layer using an acidic copper sulfate based plating solution. The plot **700** illustrates that the collimator may be used to control the plating uniformity, i.e., the edge of the substrate has reduced plating thickness, as illustrated by **702**. Additionally, the center of the substrate has reduced plating thickness **706**, while the middle portion of the substrate between the center and edge has increased plating rate **704**. This data illustrates that the collimator of the invention may be used to overcome edge high plating characteristics associated with the terminal effect.

[0057] While the foregoing is directed to embodiments of the present 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.

1. A fluid processing cell, comprising:

a fluid basin configured to contain an electrolyte solution and having an opening configured to receive a substrate for processing;

an anode assembly positioned in the fluid basin; and

a collimator positioned in the fluid basin between the anode and the opening.

2. The fluid processing cell of claim 1, wherein the collimator comprises a plurality of electrically insulative fluid conduits.

3. The fluid processing cell of claim 2, wherein the fluid conduits are positioned such that a longitudinal axis of each of the conduits is parallel to each of the other longitudinal axes of the conduits.

4. The fluid processing cell of claim 1, wherein the collimator comprises a plurality of fluid conduits positioned such that a longitudinal axis of each of the conduits is generally perpendicular to an upper surface of the anode assembly.

5. The fluid processing cell of claim 3, wherein an upper terminating end of the conduits is positioned between about 0.5 mm and about 15 mm from a substrate processing position.

6. The fluid processing cell of claim 5, wherein a lower terminating end of the conduits is positioned between about 0.5 mm and about 15 mm from at least one of the anode assembly and a membrane positioned across the fluid basin between the anode assembly and the opening.

7. The fluid processing cell of claim 6, wherein a horizontal cross section of an individual conduit is at least one of a circle, square, triangle, hexagon, pentagon, or other polygon.

8. The fluid processing cell of claim 2, wherein the fluid conduits are circular and have an interior diameter of between about 1 mm and about 10 mm.

9. The fluid processing cell of claim 1, wherein the anode assembly comprises a plurality of individually powered polygon shaped anode members that cooperatively form a substantially planar upper anode surface.

10. An electrochemical plating cell, comprising:

a cell body configured to contain a plating solution therein and having an opening configured to receive a substrate for plating;

an anode assembly positioned in the cell body such that the anode assembly is in electrical communication with the plating solution; and

an electric field collimator positioned in the cell body between the anode assembly and the opening, the collimator comprising a plurality of electrically insulative fluid conduits having substantially parallel longitudinal axes.

11. The electrochemical plating cell of claim 10, wherein each of the plurality of electrically insulative fluid conduits has an inner diameter of less than about 20 mm.

12. The electrochemical plating cell of claim 10, wherein each of the plurality of electrically insulative fluid conduits has an inner diameter of between about 1 mm and about 10 mm.

13. The electrochemical plating cell of claim 10, wherein an upper surface of the electric field collimator is positioned between about 0.5 mm and about 20 mm from a substrate processing position.

14. The electrochemical plating cell of claim 10, wherein a lower surface of the electric field collimator is positioned between about 2 mm and about 20 mm from at least one of an upper surface of the anode assembly and a membrane positioned across the cell body between the anode assembly and the opening.

15. The electrochemical plating cell of claim 10, wherein the electric field collimator comprises more than about 500 electrically insulative fluid conduits.

16. The electrochemical plating cell of claim 15, wherein the diameter of the collimator is between about 275 mm and about 325 mm.

17. The electrochemical plating cell of claim 16, wherein the opening is sized to receive a substrate having a diameter greater than about 275 mm.

18. The electrochemical plating cell of claim 10, wherein the electric field collimator occupies between about 50% and about 99% of vertical space between the anode assembly and the substrate.

19. The electrochemical plating cell of claim 10, wherein the electric field collimator comprises a disk shaped insulative material having a plurality of bores formed therethrough which define the fluid conduits.

20. The electrochemical plating system of claim 10, wherein the anode assembly comprises a plurality of individually powered square shaped anode members, each of the square shaped anode members having an electrically insulating spacer positioned around the perimeter thereof.

21. A method for plating a conductive material onto a substrate, comprising:

generating an electric field between an anode positioned in a plating cell and a substrate being plated in the plating cell;

collimating the electric field in a substantially linear direction between the anode and the substrate; and

plating the conductive material onto the substrate.

22. The method of claim 21, wherein collimating further comprises:

receiving the electric field into a first opening of an electrically insulating collimator;

transmitting the electric field to a second opening of the collimator via a substantially linear fluid conduit connecting the first and second openings; and

transmitting the electric field toward the substrate from the second opening.

23. The method of claim 22, wherein the second opening is positioned between about 0.5 mm and about 20 mm from the substrate.

24. The method of claim 22, wherein the first opening is positioned between about 1 mm and about 20 mm from the anode.

25. The method of claim 22, wherein the substantially linear fluid conduit connecting the first and second openings has a longitudinal axis that is generally perpendicular to an upper surface of the anode.

26. The method of claim 22, wherein the electrically insulating collimator occupies between about 50% and about 99% of vertical space between the anode and the substrate.

27. The method of claim 21, generating the electric field comprises individually powering a plurality of polygon shaped anode members.

28. The method of claim 27, further comprising controlling plating uniformity by controlling power application to the individual anode members.

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