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(54) METHODS AND APPARATUS FOR REMOVING CONDUCTIVE MATERIAL FROM A MICROELECTRONIC SUBSTRATE

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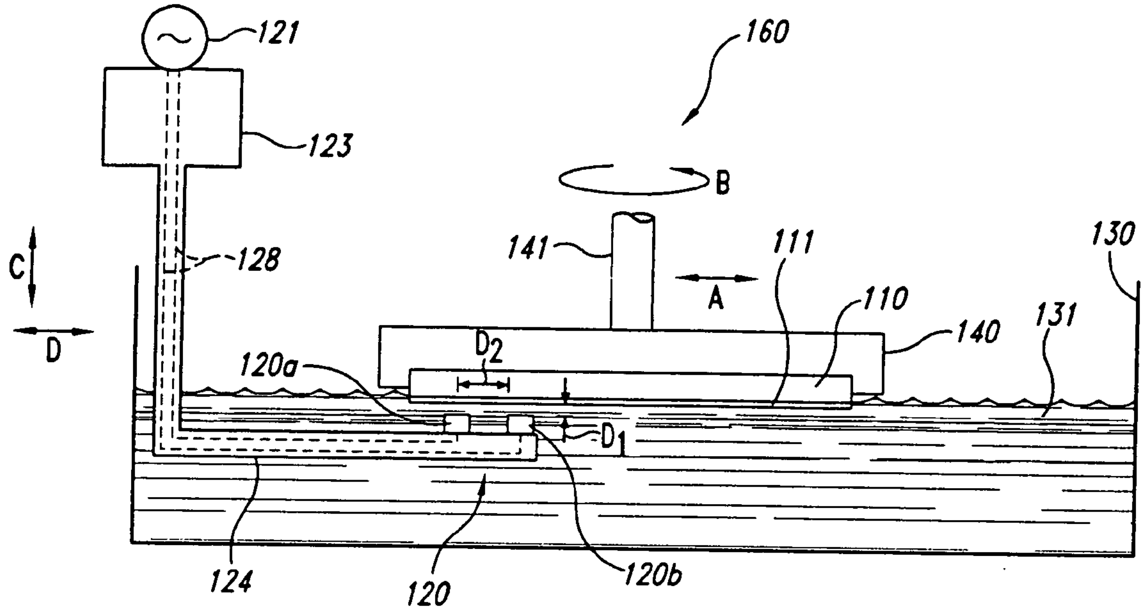
(57) ABSTRACT

A method and apparatus for removing conductive material from a microelectronic substrate. In one embodiment, a support member supports a microelectronic substrate relative to first and second electrodes, which are spaced apart from each other and spaced apart from the microelectronic substrate. One or more electrolytes are disposed between the electrodes and the microelectronic substrate to electrically link the electrodes to the microelectronic substrate. The electrodes are then coupled to a source of varying current that electrically removes the conductive material from the substrate. The microelectronic substrate and/or the electrodes can be moved relative to each other to position the electrodes relative to a selected portion of the microelectronic substrate, and the electrodes can be integrated with a planarizing portion of the apparatus to remove material from the conductive layer by chemical-mechanical planarization.



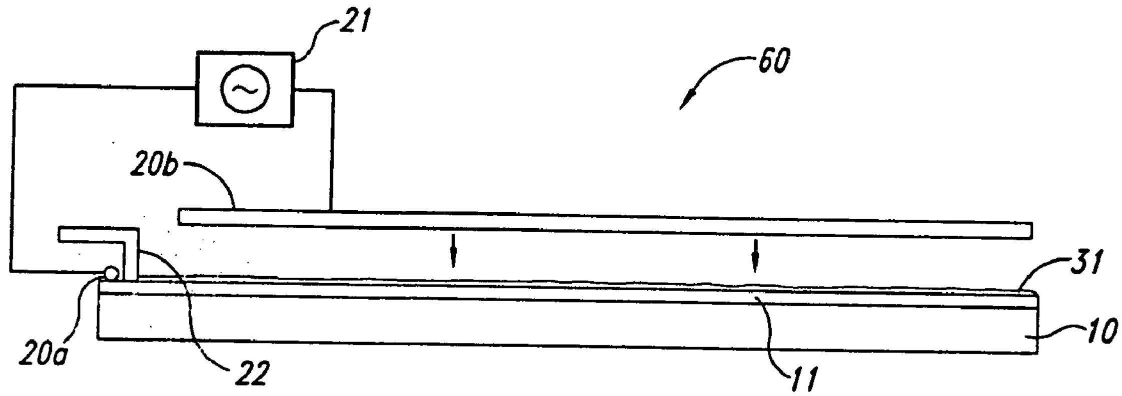


Fig. 1
(Prior Art)

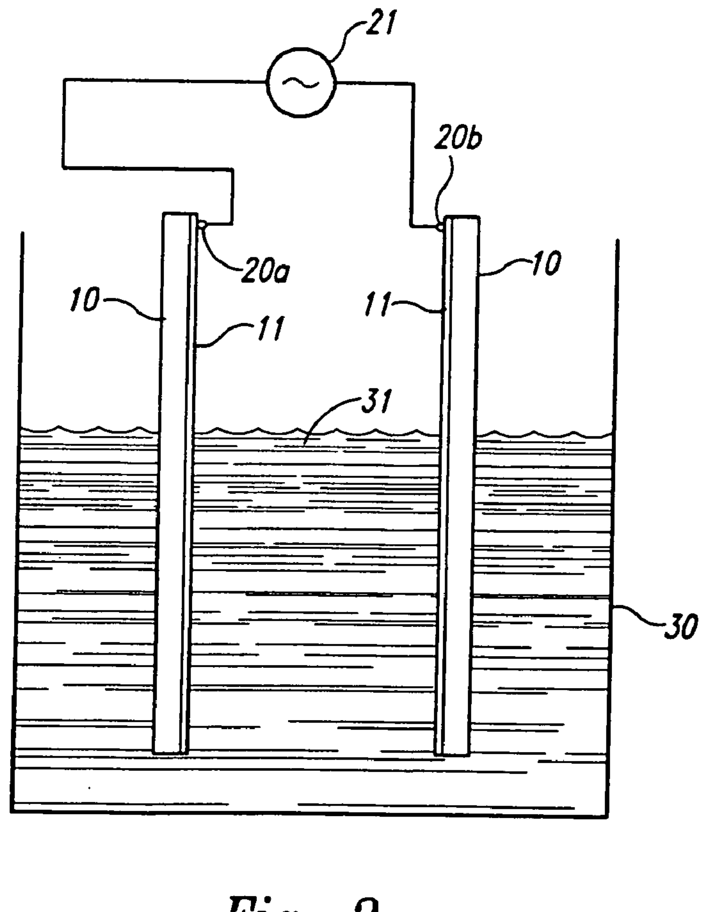


Fig. 2
(Prior Art)

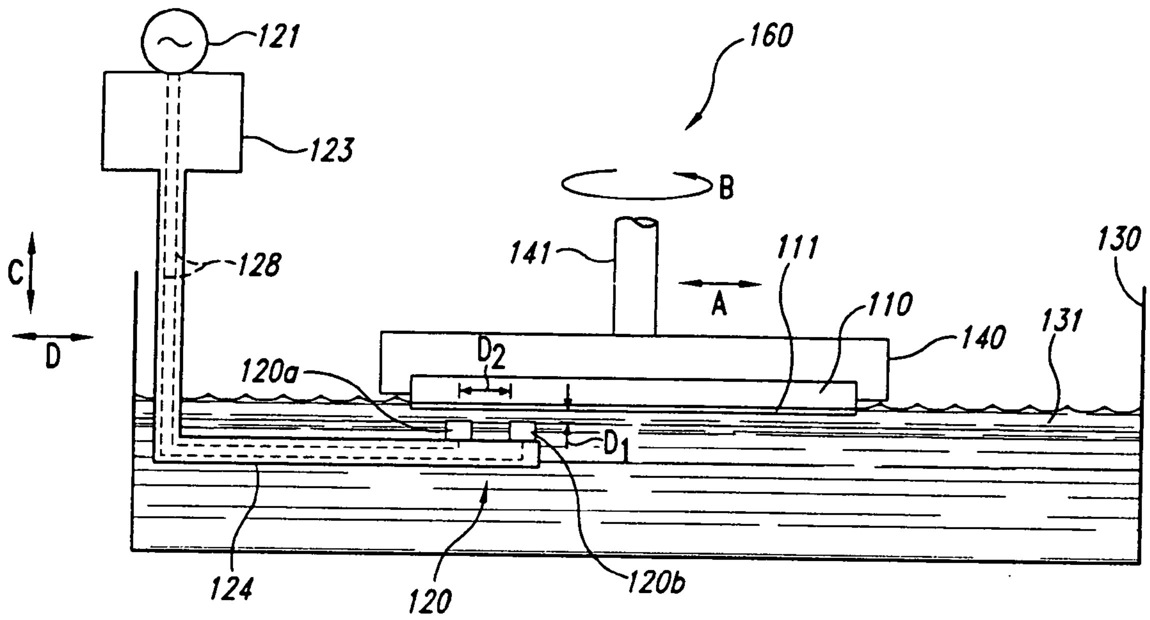

121
160
123
B
141
111
130
C
128
A
110
D
D2
140
131
120a
D1
124
120
120b

Fig. 3

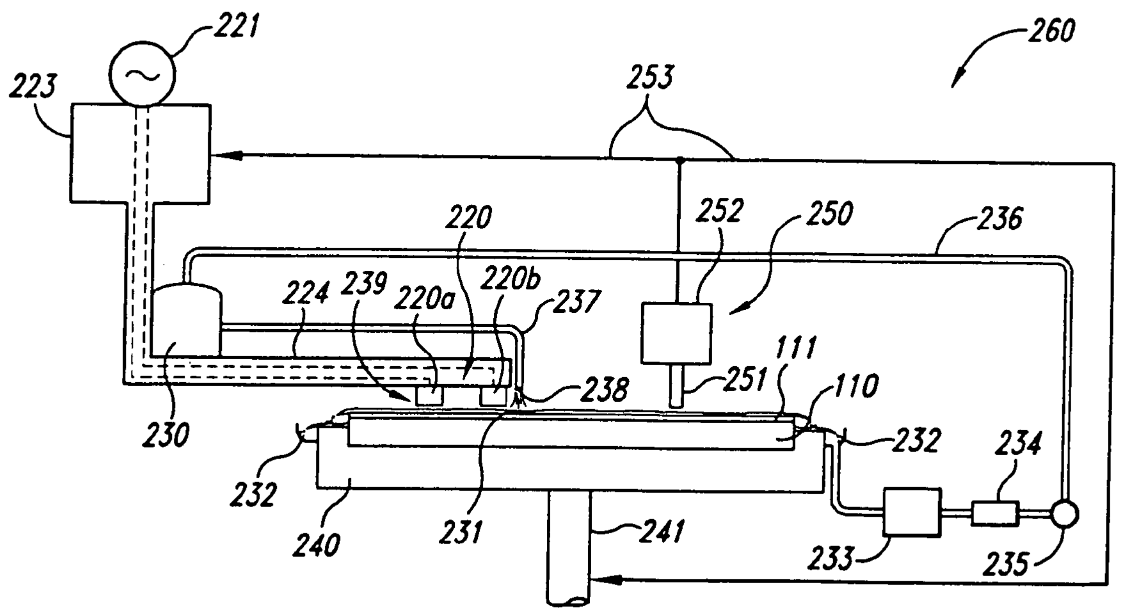

221
260
223
253
252
250
236
220
224
239
220a
220b
237
111
251
110
230
238
232
234
232
240
231
241
233
235

Fig. 4

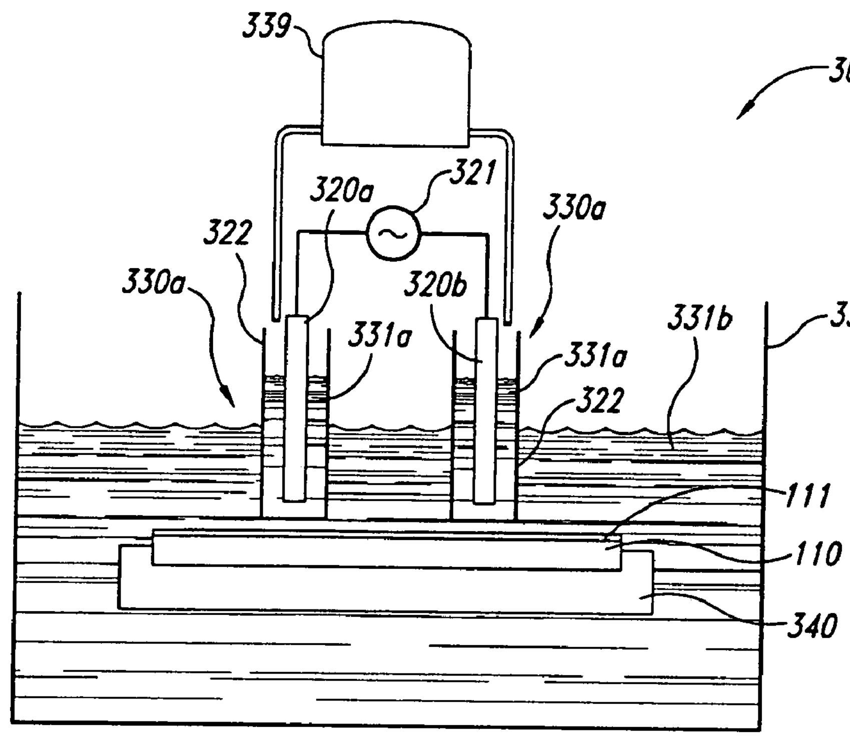

339
360
321
320a
330a
322
330a
320b
331b
330b
331a
331a
322
111
110
340

Fig. 5

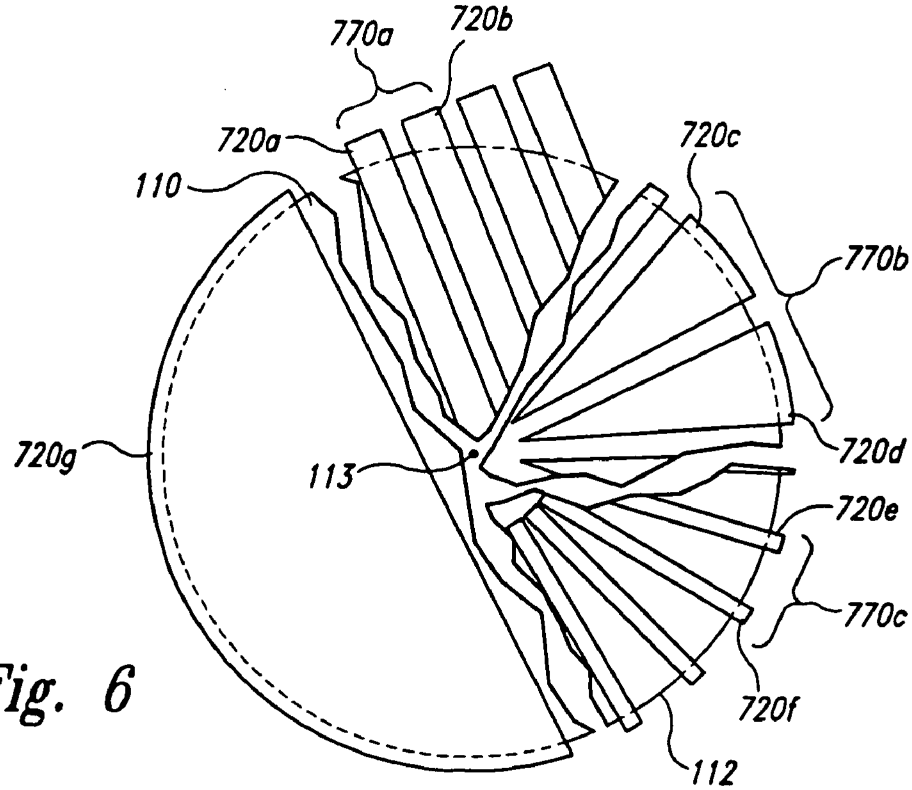

770a
720b
720a
720c
110
770b
720d
720g
113
720e
770c
720f
112

Fig. 6

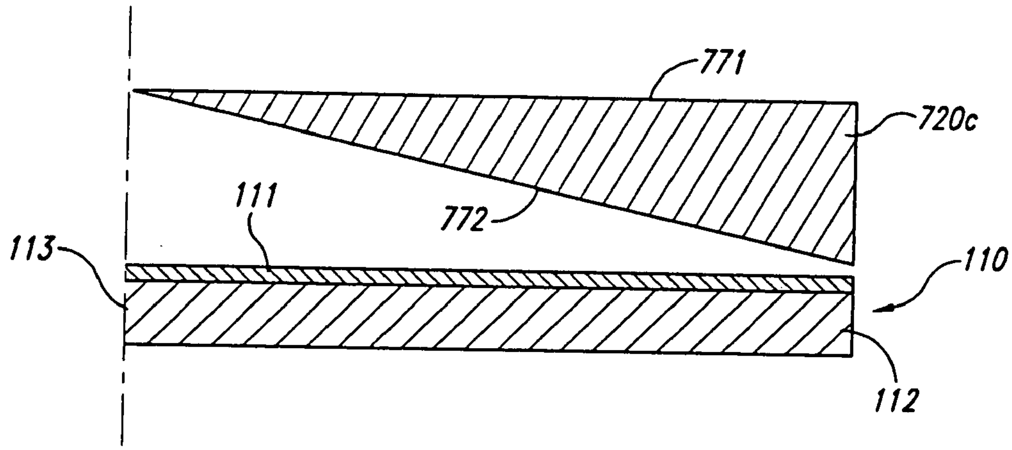

771
720c
111
772
113
110
112

Fig. 7

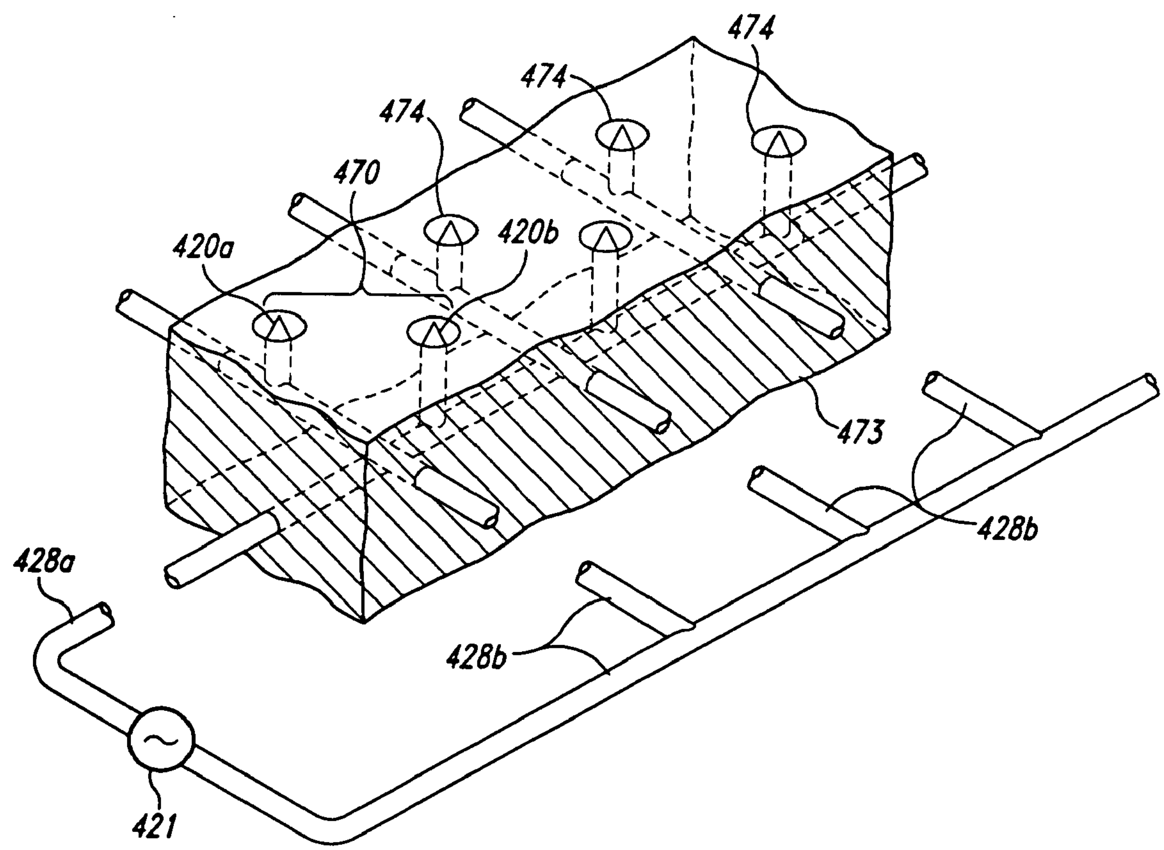

474
474
474
470
420a
420b
473
428b
428a
428b
421

Fig. 8A

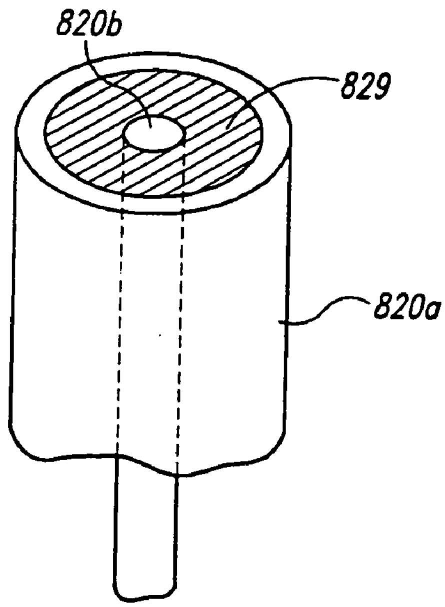


Fig. 8B

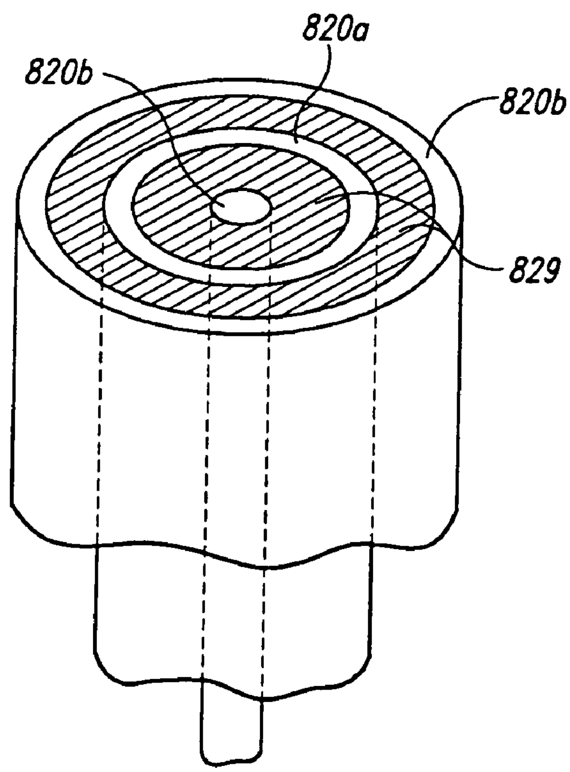


Fig. 8C

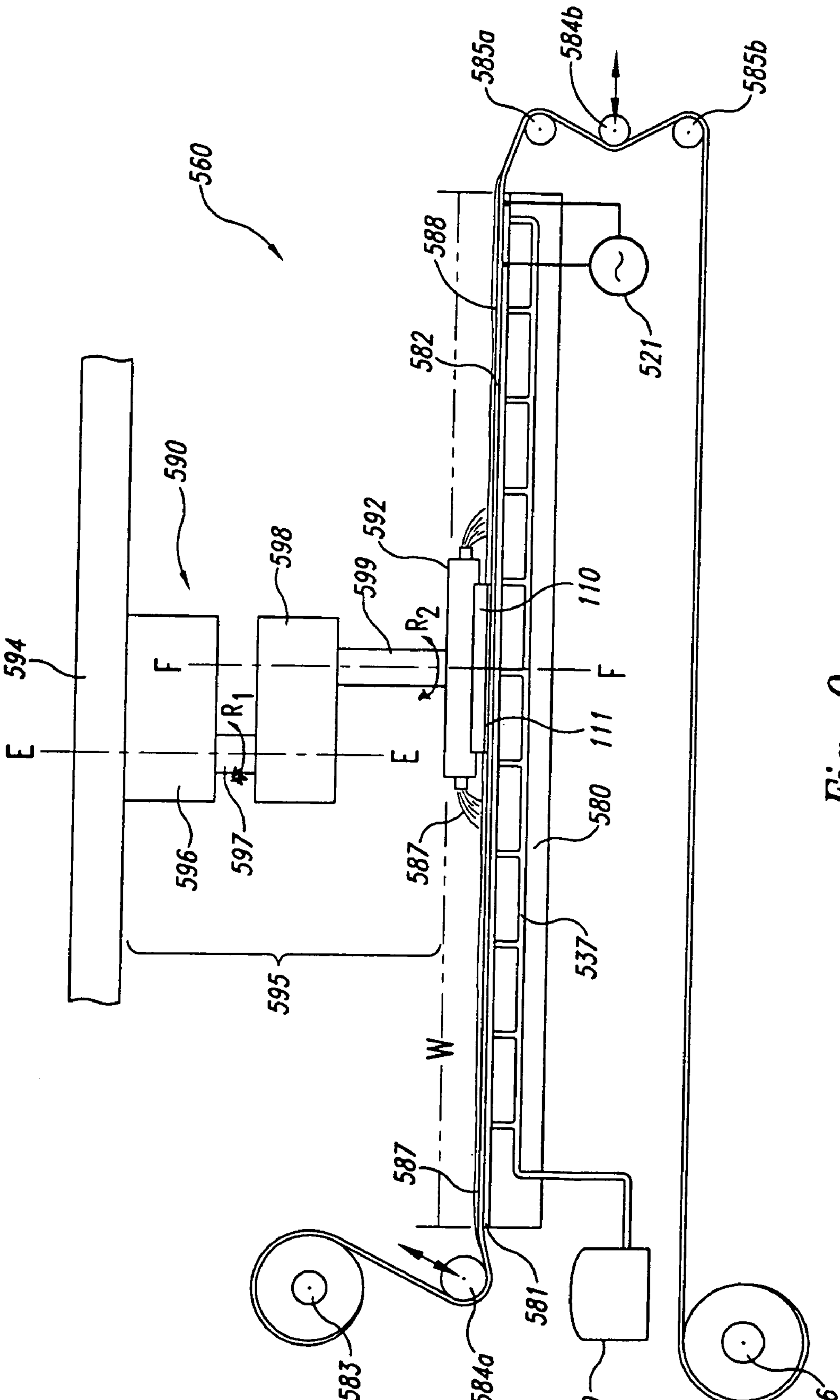

560
585a
584b
585b
588
521
582
590
594
598
599
592
R_2
110
F
F
E
E
R_1
111
596
597
587
580
537
595
W
587
581
583
584a
530
586

Fig. 9

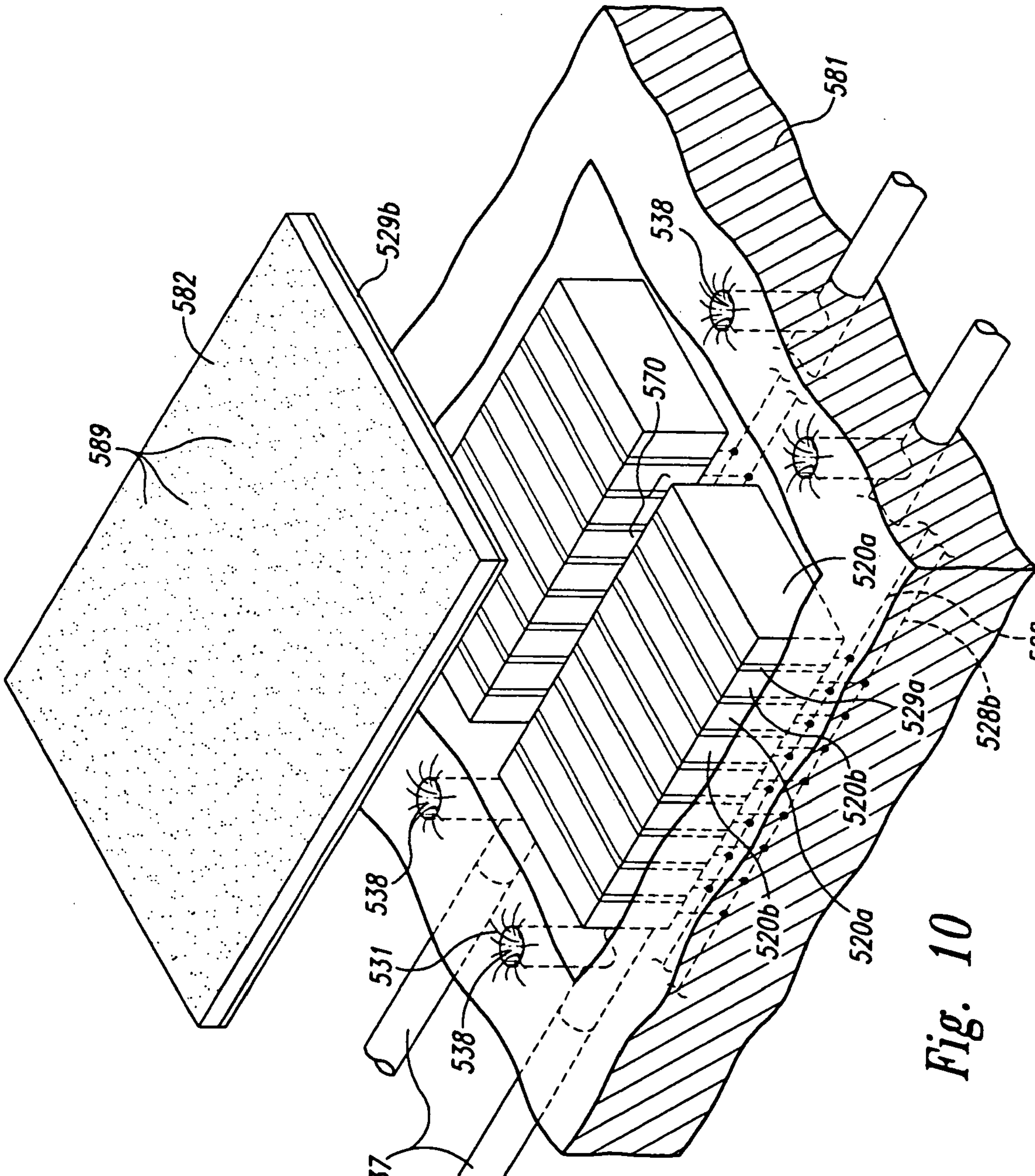

581
538
529b
582
589
570
520a
528a
529a
528b
520b
520b
520a
538
531
538
537

Fig. 10

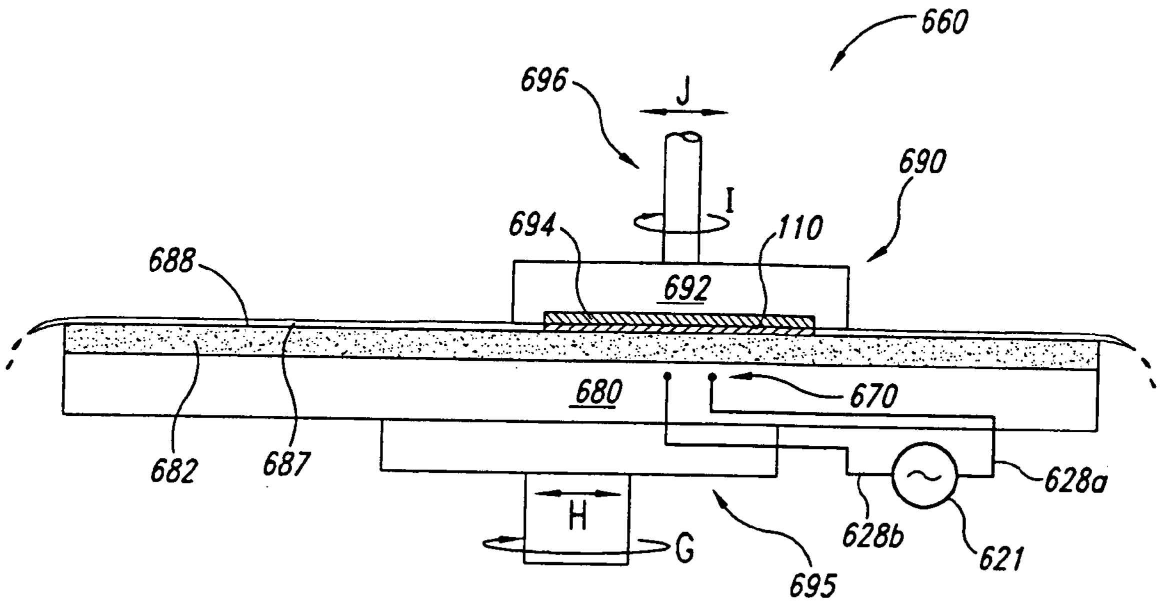


Fig. 11

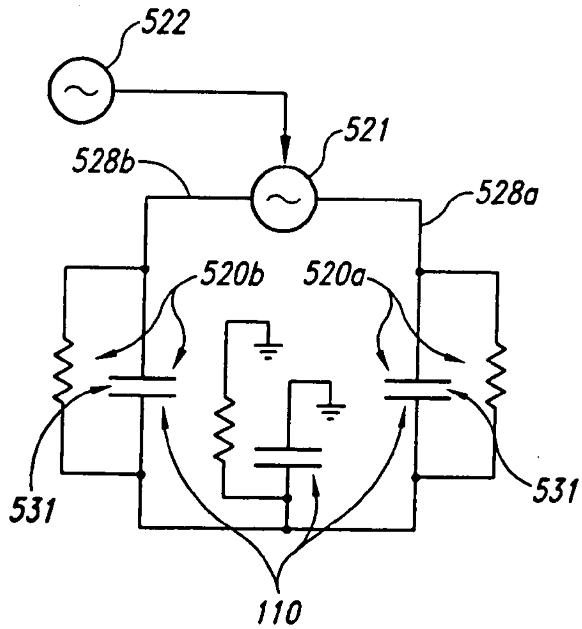


Fig. 12A

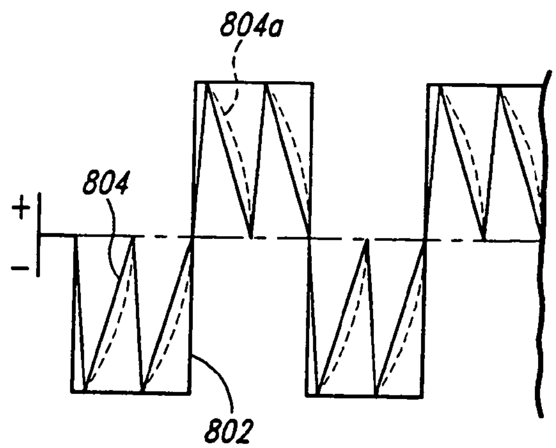


Fig. 12B

METHODS AND APPARATUS FOR REMOVING CONDUCTIVE MATERIAL FROM A MICROELECTRONIC SUBSTRATE

TECHNICAL FIELD

[0001] This invention relates to methods and apparatuses for removing conductive material from microelectronic substrates.

BACKGROUND OF THE INVENTION

[0002] Microelectronic substrates and substrate assemblies typically include a semiconductor material having features, such as memory cells, that are linked with conductive lines. The conductive lines can be formed by first forming trenches or other recesses in the semiconductor material, and then overlaying a conductive material (such as a metal) in the trenches. The conductive material is then selectively removed to leave conductive lines extending from one feature in the semiconductor material to another.

[0003] Electrolytic techniques have been used to both deposit and remove metallic layers from semiconductor substrates. For example, an alternating current can be applied to a conductive layer via an intermediate electrolyte to remove portions of the layer. In one arrangement, shown in **FIG. 1**, a conventional apparatus **60** includes a first electrode **20***a* and a second electrode **20***b* coupled to a current source **21**. The first electrode **20***a* is attached directly to a metallic layer **11** of a semiconductor substrate **10** and the second electrode **20***b* is at least partially immersed in a liquid electrolyte **31** disposed on the surface of the metallic layer **11** by moving the second electrode downwardly until it contacts the electrolyte **31**. A barrier **22** protects the first electrode **20***a* from direct contact with the electrolyte **31**. The current source **21** applies alternating current to the substrate **10** via the electrodes **20***a* and **20***b* and the electrolyte **31** to remove conductive material from the conductive layer **11**. The alternating current signal can have a variety of wave forms, such as those disclosed by Frankenthal et al. in a publication entitled, "Electroetching of Platinum in the Titanium-Platinum-Gold Metallization on Silicon Integrated Circuits" (Bell Laboratories), incorporated herein in its entirety by reference.

[0004] One drawback with the arrangement shown in **FIG. 1** is that it may not be possible to remove material from the conductive layer **11** in the region where the first electrode **20***a* is attached because the barrier **22** prevents the electrolyte **31** from contacting the substrate **10** in this region. Alternatively, if the first electrode **20***a* contacts the electrolyte in this region, the electrolytic process can degrade the first electrode **20***a*. Still a further drawback is that the electrolytic process may not uniformly remove material from the substrate **10**. For example, "islands" of residual conductive material having no direct electrical connection to the first electrode **20***a* may develop in the conductive layer **11**. The residual conductive material can interfere with the formation and/or operation of the conductive lines, and it may be difficult or impossible to remove with the electrolytic process unless the first electrode **20***a* is repositioned to be coupled to such "islands."

[0005] One approach to addressing some of the foregoing drawbacks is to attach a plurality of first electrodes **20***a* around the periphery of the substrate **10** to increase the uniformity with which the conductive material is removed. However, islands of conductive material may still remain despite the additional first electrodes **20***a*. Another approach is to form the electrodes **20***a* and **20***b* from an inert material, such as carbon, and remove the barrier **22** to increase the area of the conductive layer **11** in contact with the electrolyte **31**. However, such inert electrodes may not be as effective as more reactive electrodes at removing the conductive material, and the inert electrodes may still leave residual conductive material on the substrate **10**.

[0006] **FIG. 2** shows still another approach to addressing some of the foregoing drawbacks in which two substrates **10** are partially immersed in a vessel **30** containing the electrolyte **31**. The first electrode **20***a* is attached to one substrate **10** and the second electrode **20***b* is attached to the other substrate **10**. An advantage of this approach is that the electrodes **20***a* and **20***b* do not contact the electrolyte. However, islands of conductive material may still remain after the electrolytic process is complete, and it may be difficult to remove conductive material from the points at which the electrodes **20***a* and **20***b* are attached to the substrates **10**.

SUMMARY

[0007] The present invention is directed toward methods and apparatuses for removing conductive materials from microelectronic substrates. A method in accordance with one aspect of the invention includes positioning a first conductive electrode proximate to the microelectronic substrate and positioning a second conductive electrode proximate to the microelectronic substrate and spaced apart from the first conductive electrode. The method further includes removing the conductive material from the microelectronic substrate by applying a varying current to at least one of the first and second electrodes while the first and second electrodes are spaced apart from the conductive material of the microelectronic substrate.

[0008] In a further aspect of the invention, the method can include disposing a dielectric layer between the microelectronic substrate and the first electrode and/or varying an amplitude of the current at a first frequency while superimposing on the first frequency an amplitude and/or polarity variation having a second frequency less than the first frequency. The rate at which conductive material is removed from the microelectronic substrate can be controlled by controlling a distance between at least one of the electrodes and the microelectronic substrate. The microelectronic substrate and/or the electrodes can be moved relative to each other to position the electrode at a selected position relative to the microelectronic substrate. In yet another aspect of the invention, a first electrolyte adjacent to the electrodes can be separated from a second electrolyte adjacent to the microelectronic substrate while maintaining an electrical connection between the electrolytes.

[0009] The invention is also directed toward an apparatus for removing conductive material from a microelectronic substrate. The apparatus can include a support member having at least one engaging surface to support the microelectronic substrate, and first and second electrodes. The first and second electrodes are spaced apart from the support member and the microelectronic substrate when the microelectronic substrate is supported by the support member, and

at least one of the first and second electrodes is coupleable to a source of varying current. The electrodes can have a planform shape that corresponds to a planform shape of a portion of the microelectronic substrates and they can be arranged in pairs with the pairs distributed to control the distance between the electrodes and the microelectronic substrate. The apparatus can further include a sensor positioned at least proximate to the support member to detect the rate at which the conductive material is removed from the microelectronic substrate and/or the amount of conductive material remaining on the microelectronic substrate. In still a further aspect of this embodiment, a polishing pad can be positioned proximate to the support member and can include a polishing surface for removing material from the microelectronic substrate by chemical and/or chemical-mechanical planarization as the polishing pad and/or the microelectronic substrate move relative to each other.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] **FIG. 1** is a partially schematic, side elevational view of an apparatus for removing conductive material from a semiconductor substrate in accordance with the prior art.

[0011] **FIG. 2** is a partially schematic side, elevational view of another apparatus for removing conductive material from two semiconductor substrates in accordance with the prior art.

[0012] **FIG. 3** is a partially schematic, side elevational view of an apparatus having a support member and a pair of electrodes for removing conductive material from a microelectronic substrate in accordance with an embodiment of the invention.

[0013] **FIG. 4** is a partially schematic, side elevational view of an apparatus for removing conductive material and sensing characteristics of the microelectronic substrate from which the material is removed in accordance with another embodiment of the invention.

[0014] **FIG. 5** is a partially schematic, side elevational view of an apparatus that includes two electrolytes in accordance with still another embodiment of the invention.

[0015] **FIG. 6** is a partially schematic, plan view of a substrate adjacent to a plurality of electrodes in accordance with still further embodiments of the invention.

[0016] **FIG. 7** is a cross-sectional, side elevational view of an electrode and a substrate in accordance with yet another embodiment of the invention.

[0017] **FIG. 8A** is a partially schematic, isometric view of a portion of a support for housing electrode pairs in accordance with still another embodiment of the invention.

[0018] **FIGS. 8B-8C** are isometric views of electrodes in accordance with still further embodiments of the invention.

[0019] **FIG. 9** is a partially schematic, side elevational view of an apparatus for both planarizing and electrolytically processing microelectronic substrates in accordance with yet another embodiment of the invention.

[0020] **FIG. 10** is a partially schematic, partially exploded isometric view of a planarizing pad and a plurality of electrodes in accordance with still another embodiment of the invention.

[0021] **FIG. 11** is a partially schematic, side elevational view of an apparatus for both planarizing and electrolytically processing microelectronic substrates in accordance with still another embodiment of the invention.

[0022] FIGS. **12**A-B schematically illustrate a circuit and wave form for electrolytically processing a microelectronic substrate in accordance with yet another embodiment of the invention.

DETAILED DESCRIPTION

[0023] The present disclosure describes methods and apparatuses for removing conductive materials from a microelectronic substrate and/or substrate assembly used in the fabrication of microelectronic devices. Many specific details of certain embodiments of the invention are set forth in the following description and in **FIGS. 3-12B** to provide a thorough understanding of these embodiments. One skilled in the art, however, will understand that the present invention may have additional embodiments, or that the invention may be practiced without several of the details described below.

[0024] **FIG. 3** is a partially schematic, side elevational view of an apparatus **160** for removing conductive material from a microelectronic substrate or substrate assembly **110** in accordance with an embodiment of the invention. In one aspect of this embodiment, the apparatus **160** includes a vessel **130** containing an electrolyte **131**, which can be in a liquid or a gel state. A support member **140** supports the microelectronic substrate **110** relative to the vessel **130** so that a conductive layer **111** of the substrate **110** contacts the electrolyte **131**. The conductive layer **111** can include metals such as platinum, tungsten, tantalum, gold, copper, or other conductive materials. In another aspect of this embodiment, the support member **140** is coupled to a substrate drive unit **141** that moves the support member **140** and the substrate **110** relative to the vessel **130**. For example, the substrate drive unit **141** can translate the support member **140** (as indicated by arrow "A") and/or rotate the support member **140** (as indicated by arrow "B").

[0025] The apparatus **160** can further include a first electrode **120*a*** and a second electrode **120*b*** (referred to collectively as electrodes **120**) supported relative to the microelectronic substrate **110** by a support member **124**. In one aspect of this embodiment, the support arm **124** is coupled to an electrode drive unit **123** for moving the electrodes **120** relative to the microelectronic substrate **110**. For example, the electrode drive unit **123** can move the electrodes toward and away from the conductive layer **111** of the microelectronic substrate **110**, (as indicated by arrow "C"), and/or transversely (as indicated by arrow "D") in a plane generally parallel to the conductive layer **111**. Alternatively, the electrode drive unit **123** can move the electrodes in other fashions, or the electrode drive unit **123** can be eliminated when the substrate drive unit **141** provides sufficient relative motion between the substrate **110** and the electrodes **120**.

[0026] In either embodiment described above with reference to **FIG. 3**, the electrodes **120** are coupled to a current source **121** with leads **128** for supplying electrical current to the electrolyte **131** and the conductive layer **111**. In operation, the current source **121** supplies an alternating current (single phase or multiphase) to the electrodes **120**. The current passes through the electrolyte **131** and reacts electrochemically with the conductive layer **111** to remove material (for example, atoms or groups of atoms) from the conductive layer **111**. The electrodes **120** and/or the substrate **110** can be moved relative to each other to remove material from selected portions of the conductive layer **111**, or from the entire conductive layer **111**.

[**0027**] In one aspect of an embodiment of the apparatus **160** shown in **FIG. 3**, a distance D_1 between the electrodes **120** and the conductive layer **111** is set to be smaller than a distance D_2 between the first electrode **120***a* and the second electrode **120***b*. Furthermore, the electrolyte **131** generally has a higher resistance than the conductive layer **111**. Accordingly, the alternating current follows the path of least resistance from the first electrode **120***a*, through the electrolyte **131** to the conductive layer **111** and back through the electrolyte **131** to the second electrode **120***b*, rather than from the first electrode **120***a* directly through the electrolyte **131** to the second electrode **120***b*. Alternatively, a low dielectric material (not shown) can be positioned between the first electrode **120***a* and the second electrode **120***b* to decouple direct electrical communication between the electrodes **120** that does not first pass through the conductive layer **111**.

[**0028**] One feature of an embodiment of the apparatus **160** shown in **FIG. 3** is that the electrodes **120** do not contact the conductive layer **111** of the substrate **110**. An advantage of this arrangement is that it can eliminate the residual conductive material resulting from a direct electrical connection between the electrodes **120** and the conductive layer **111**, described above with reference to **FIGS. 1 and 2**. For example, the apparatus **160** can eliminate residual conductive material adjacent to the contact region between the electrodes and the conductive layer because the electrodes **120** do not contact the conductive layer **111**.

[**0029**] Another feature of an embodiment of the apparatus **160** described above with reference to **FIG. 3** is that the substrate **110** and/or the electrodes **120** can move relative to the other to position the electrodes **120** at any point adjacent to the conductive layer **111**. An advantage of this arrangement is that the electrodes **120** can be sequentially positioned adjacent to every portion of the conductive layer to remove material from the entire conductive layer **111**. Alternatively, when it is desired to remove only selected portions of the conductive layer **111**, the electrodes **120** can be moved to those selected portions, leaving the remaining portions of the conductive layer **111** intact.

[**0030**] **FIG. 4** is a partially schematic, side elevational view of an apparatus **260** that includes a support member **240** positioned to support the substrate **110** in accordance with another embodiment of the invention. In one aspect of this embodiment, the support member **240** supports the substrate **110** with the conductive layer **111** facing upwardly. A substrate drive unit **241** can move the support member **240** and the substrate **110**, as described above with reference to **FIG. 3**. First and second electrodes **220***a* and **220***b* are positioned above the conductive layer **111** and are coupled to a current source **221**. A support member **224** supports the electrodes **220** relative to the substrate **110** and is coupled to an electrode drive unit **223** to move the electrodes **220** over the surface of the support conductive layer **111** in a manner generally similar to that described above with reference to **FIG. 3**.

[**0031**] In one aspect of the embodiment shown in **FIG. 4**, the apparatus **260** further includes an electrolyte vessel **230** having a supply conduit **237** with an aperture **238** positioned proximate to the electrodes **220**. Accordingly, an electrolyte **231** can be deposited locally in an interface region **239** between the electrodes **220** and the conductive layer **111**, without necessarily covering the entire conductive layer **111**. The electrolyte **231** and the conductive material removed from the conductive layer **111** flow over the substrate **110** and collect in an electrolyte receptacle **232**. The mixture of electrolyte **231** and conductive material can flow to a reclaimer **233** that removes most of the conductive material from the electrolyte **231**. A filter **234** positioned downstream of the reclaimer **233** provides additional filtration of the electrolyte **231** and a pump **235** returns the reconditioned electrolyte **231** to the electrolyte vessel **230** via a return line **236**.

[**0032**] In another aspect of the embodiment shown in **FIG. 4**, the apparatus **260** can include a sensor assembly **250** having a sensor **251** positioned proximate to the conductive layer **111**, and a sensor control unit **252** coupled to the sensor **251** for processing signals generated by the sensor **251**. The control unit **252** can also move the sensor **251** relative to the substrate **110**. In a further aspect of this embodiment, the sensor assembly **250** can be coupled via a feedback path **253** to the electrode drive unit **223** and/or the substrate drive unit **241**. Accordingly, the sensor **251** can determine which areas of the conductive layer **111** require additional material removal and can move the electrodes **220** and/or the substrate **110** relative to each other to position the electrodes **220** over those areas. Alternatively, (for example, when the removal process is highly repeatable), the electrodes **220** and/or the substrate **110** can move relative to each other according to a pre-determined motion schedule.

[**0033**] The sensor **251** and the sensor control unit **252** can have any of a number of suitable configurations. For example, in one embodiment, the sensor **251** can be an optical sensor that detects removal of the conductive layer **111** by detecting a change in the intensity, wavelength or phase shift of the light reflected from the substrate **110** when the conductive material is removed. Alternatively, the sensor **251** can emit and detect reflections of radiation having other wavelengths, for example, x-ray radiation. In still another embodiment, the sensor **251** can measure a change in resistance or capacitance of the conductive layer **111** between two selected points. In a further aspect of this embodiment, one or both of the electrodes **220** can perform the function of the sensor **251** (as well as the material removal function described above), eliminating the need for a separate sensor **251**. In still further embodiments, the sensor **251** can detect a change in the voltage and/or current drawn from the current supply **221** as the conductive layer **111** is removed.

[**0034**] In any of the embodiments described above with reference to **FIG. 4**, the sensor **251** can be positioned apart from the electrolyte **231** because the electrolyte **231** is concentrated in the interface region **239** between the electrodes **220** and the conductive layer **111**. Accordingly, the accuracy with which the sensor **251** determines the progress of the electrolytic process can be improved because the electrolyte **231** will be less likely to interfere with the operation of the sensor **251**. For example, when the sensor **251** is an optical sensor, the electrolyte **231** will be less likely to distort the radiation reflected from the surface of the substrate **110** because the sensor **251** is positioned away from the interface region **239**.

[**0035**] Another feature of an embodiment of the apparatus **260** described above with reference to **FIG. 4** is that the electrolyte **231** supplied to the interface region **239** is continually replenished, either with a reconditioned electrolyte or a fresh electrolyte. An advantage of this feature is that the electrochemical reaction between the electrodes **220** and the conductive layer **111** can be maintained at a high and consistent level.

[**0036**] **FIG. 5** is a partially schematic, side elevational view of an apparatus **360** that directs alternating current to the substrate **110** through a first electrolyte **331***a* and a second electrolyte **331***b*. In one aspect of this embodiment, the first electrolyte **331***a* is disposed in two first electrolyte vessels **330***a*, and the second electrolyte **331***b* is disposed in a second electrolyte vessel **330***b*. The first electrolyte vessels **330***a* are partially submerged in the second electrolyte 331*b*. The apparatus **360** can further include electrodes **320**, shown as a first electrode **320***a* and a second electrode **320***b*, each coupled to a current supply **321** and each housed in one of the first electrolyte vessels **330***a*. Alternatively, one of the electrodes **320** can be coupled to ground. The electrodes **320** can include materials such as silver, platinum, copper and/or other materials, and the first electrolyte **331***a* can include sodium chloride, potassium chloride, copper sulfate and/or other electrolytes that are compatible with the material forming the electrodes **320**.

[**0037**] In one aspect of this embodiment, the first electrolyte vessels **330***a* include a flow restrictor **322**, such as a permeable isolation membrane formed from Teflon™, sintered materials such as sintered glass, quartz or sapphire, or other suitable porous materials that allow ions to pass back and forth between the first electrolyte vessels **330***a* and the second electrolyte vessel **330***b*, but do not allow the second electrolyte **330***b* to pass inwardly toward the electrodes **320** (for example, in a manner generally similar to a salt bridge). Alternatively, the first electrolyte **331***a* can be supplied to the electrode vessels **330***a* from a first electrolyte source **339** at a pressure and rate sufficient to direct the first electrolyte **331***a* outwardly through the flow restrictor **322** without allowing the first electrolyte **331***a* or the second electrolyte **330***b* to return through the flow restrictor **322**. In either embodiment, the second electrolyte 331*b* remains electrically coupled to the electrodes **320** by the flow of the first electrolyte **33** la through the restrictor **322**.

[**0038**] In one aspect of this embodiment, the apparatus **360** can also include a support member **340** that supports the substrate **110** with the conductive layer **111** facing toward the electrodes **320**. For example, the support member **340** can be positioned in the second electrolyte vessel **330***b*. In a further aspect of this embodiment, the support member **340** and/or the electrodes **320** can be movable relative to each other by one or more drive units (not shown).

[**0039**] One feature of an embodiment of the apparatus **360** described above as reference to **FIG. 5** is that the first electrolyte **331***a* can be selected to be compatible with the electrodes **320**. An advantage of this feature is that the first electrolyte **331***a* can be less likely than conventional electrolytes to degrade the electrodes **320**. Conversely, the second electrolyte **331***b* can be selected without regard to the effect it has on the electrodes **320** because it is chemically isolated from the electrodes **320** by the flow restrictor **322**. Accordingly, the second electrolyte 331*b* can include hydrochloric acid or another agent that reacts aggressively with the conductive layer **111** of the substrate **110**.

[**0040**] **FIG. 6** is a top plan view of the microelectronic substrate **110** positioned beneath a plurality of electrodes having shapes and configurations in accordance with several embodiments of the invention. For purposes of illustration, several different types of electrodes are shown positioned proximate to the same microelectronic substrate **110**; however, in practice, electrodes of the same type can be positioned relative to a single microelectronic substrate **110**.

[**0041**] In one embodiment, electrodes **720***a* and **720***b* can be grouped to form an electrode pair **770***a*, with each electrode **720***a* and **720***b* coupled to an opposite terminal of a current supply **121** (**FIG. 3**). The electrodes **770***a* and **770***b* can have an elongated or strip-type shape and can be arranged to extend parallel to each other over the diameter of the substrate **110**. The spacing between adjacent electrodes of an electrode pair **370***a* can be selected to direct the electrical current into the substrate **110**, as described above with reference to **FIG. 3**.

[**0042**] In an alternate embodiment, electrodes **720***c* and **720***d* can be grouped to form an electrode pair **770***b*, and each electrode **720***c* and **720***d* can have a wedge or "pie" shape that tapers inwardly toward the center of the microelectronic substrate **110**. In still another embodiment, narrow, strip-type electrodes **720***e* and **720***f* can be grouped to form electrode pairs **770***c*, with each electrode **720***e* and **720***f* extending radially outwardly from the center **113** of the microelectronic substrate **110** toward the periphery **112** of the microelectronic substrate **110**.

[**0043**] In still another embodiment, a single electrode **720***g* can extend over approximately half the area of the microelectronic substrate **110** and can have a semicircular planform shape. The electrode **720***g* can be grouped with another electrode (not shown) having a shape corresponding to a mirror image of the electrode **720***g*, and both electrodes can be coupled to the current source **121** to provide alternating current to the microelectronic substrate in any of the manners described above with reference to **FIGS. 3-5**.

[**0044**] **FIG. 7** is a partially schematic, cross-sectional side elevational view of a portion of the substrate **110** positioned beneath the electrode **720***c* described above with reference to **FIG. 6**. In one aspect of this embodiment, the electrode **720***c* has an upper surface **771** and a lower surface **772** opposite the upper surface **771** and facing the conductive layer **111** of the substrate **110**. The lower surface **772** can taper downwardly from the center **113** of the substrate **110** toward the perimeter **112** of the substrate **110** in one aspect of this embodiment to give the electrode **720***c* a wedge-shaped profile. Alternatively, the electrode **720***c* can have a plate-type configuration with the lower surface **772** positioned as shown in **FIG. 7** and the upper surface **771** parallel to the lower surface **772**. One feature of either embodiment is that the electrical coupling between the electrode **720***c* and the substrate **110** can be stronger toward the periphery **112** of the substrate **110** than toward the center **113** of the substrate **110**. This feature can be advantageous when the periphery **112** of the substrate **110** moves relative to the electrode **720***c* at a faster rate than does the center **113** of the substrate **110**, for example, when the substrate **110** rotates about its center **113**. Accordingly, the electrode **720***c* can be shaped to account for relative motion between the electrode and the substrate **110**.

[**0045**] In other embodiments, the electrode **720***c* can have other shapes. For example, the lower surface **772** can have a curved rather than a flat profile. Alternatively, any of the electrodes described above with reference to **FIG. 6** (or other electrodes having shapes other than those shown in **FIG. 6**) can have a sloped or curved lower surface. In still further embodiments, the electrodes can have other shapes that account for relative motion between the electrodes and the substrate **110**.

[**0046**] **FIG. 8A** is a partially schematic view of an electrode support **473** for supporting a plurality of electrodes in accordance with another embodiment of the invention. In one aspect of this embodiment, the electrode support **473** can include a plurality of electrode apertures **474**, each of which houses either a first electrode **420***a* or a second electrode **420***b*. The first electrodes **420***a* are coupled through the apertures **474** to a first lead **428***a* and the second electrodes **420***b* are coupled to a second lead **428***b*. Both of the leads **428***a* and **428***b* are coupled to a current supply **421**. Accordingly, each pair **470** of first and second electrodes **420***a* and **420***b* defines part of a circuit that is completed by the substrate **110** and the electrolyte(s) described above with reference to **FIGS. 3-5**.

[**0047**] In one aspect of this embodiment, the first lead **428***a* can be offset from the second lead **428***b* to reduce the likelihood for short circuits and/or capacitive coupling between the leads. In a further aspect of this embodiment, the electrode support **473** can have a configuration generally similar to any of those described above with reference to **FIGS. 1-7**. For example, any of the individual electrodes (e.g., **320***a*, **320***c*, **320***e*, or **320***g*) described above with reference to **FIG. 6** can be replaced with an electrode support **473** having the same overall shape and including a plurality of apertures **474**, each of which houses one of the first electrodes **420***a* or the second electrodes **420***b*.

[**0048**] In still a further aspect of this embodiment, the electrode pairs **470** shown in **FIG. 8A** can be arranged in a manner that corresponds to the proximity between the electrodes **420***a*, **420***b* and the microelectronic substrate **110** (**FIG. 7**), and/or the electrode pairs **470** can be arranged to correspond to the rate of relative motion between the electrodes **420***a*, **420***b* and the microelectronic substrate **110**. For example, the electrode pairs **470** can be more heavily concentrated in the periphery **112** of the substrate **110** or other regions where the relative velocity between the electrode pairs **470** and the substrate **110** is relatively high (see **FIG. 7**). Accordingly, the increased concentration of electrode pairs **470** can provide an increased electrolytic current to compensate for the high relative velocity. Furthermore, the first electrode **420***a* and the second electrode **420***b* of each electrode pair **470** can be relatively close together in regions (such as the periphery **112** of the substrate **110**) where the electrodes are close to the conductive layer **111** (see **FIG. 7**) because the close proximity to the conductive layer **111** reduces the likelihood for direct electrical coupling between the first electrode **420***a* and the second electrode **420***b*. In still a further aspect of this embodiment, the amplitude, frequency and/or waveform shape supplied to different electrode pairs **470** can vary depending on factors such as the spacing between the electrode pair **470** and the microelectronic substrate **110**, and the relative velocity between the electrode pair **470** and the microelectronic substrate **110**.

[**0049**] **FIGS. 8B-8C** illustrate electrodes **820** (shown as first electrodes **820***a* and second electrodes **820***b*) arranged concentrically in accordance with still further embodiments of the invention. In one embodiment shown in **FIG. 8B**, the first electrode **820***a* can be positioned concentrically around the second electrode **820***b*, and a dielectric material **829** can be disposed between the first electrode **820***a* and the second electrode **820***b*. The first electrode **820***a* can define a complete 360° arc around the second electrode **820***b*, as shown in **FIG. 8B**, or alternatively, the first electrode **820***a* can define an arc of less than 360°.

[**0050**] In another embodiment, shown in **FIG. 8C**, the first electrode **820**A can be concentrically disposed between two second electrodes **820***b*, with the dielectric material **829** disposed between neighboring electrodes **820**. In one aspect of this embodiment, current can be supplied to each of the second electrodes **820***b* with no phase shifting. Alternatively, the current supplied to one second electrode **820***b* can be phase-shifted relative to the current supplied to the other second electrode **820***b*. In a further aspect of the embodiment, the current supplied to each second electrode **820***b* can differ in characteristics other than phase, for example, amplitude.

[**0051**] One feature of the electrodes **820** described above with respect to **FIGS. 8B-8C** is that the first electrode **820***a* can shield the second electrode(s) **820***b* from interference from other current sources. For example, the first electrode **820***a* can be coupled to ground to shield the second electrodes **820***b*. An advantage of this arrangement is that the current applied to the substrate **110** (**FIG. 7**) via the electrodes **820** can be more accurately controlled.

[**0052**] **FIG. 9** schematically illustrates an apparatus **560** for both planarizing and electrolytically processing the microelectronic substrate **110** in accordance with an embodiment of the invention. In one aspect of this embodiment, the apparatus **560** has a support table **580** with a top-panel **581** at a workstation where an operative portion "W" of a planarizing pad **582** is positioned. The top-panel **581** is generally a rigid plate to provide a flat, solid surface to which a particular section of the planarizing pad **582** may be secured during planarization.

[**0053**] The apparatus **560** can also have a plurality of rollers to guide, position and hold the planarizing pad **582** over the top-panel **581**. The rollers can include a supply roller **583**, first and second idler rollers **584***a* and **584***b*, first and second guide rollers **585***a* and **585***b*, and a take-up roller **586**. The supply roller **583** carries an unused or pre-operative portion of the planarizing pad **582**, and the take-up roller **583** carries a used or post-operative portion of the planarizing pad **582**. Additionally, the first idler roller **584***a* and the first guide roller **585***a* can stretch the planarizing pad **582** over the top-panel **581** to hold the planarizing pad **582** stationary during operation. A motor (not shown) drives at least one of the supply roller **583** and the take-up roller **586** to sequentially advance the planarizing pad **582** across the top-panel **581**. Accordingly, clean pre-operative sections of the planarizing pad **582** may be quickly substituted for used sections to provide a consistent surface for planarizing and/or cleaning the substrate **110**.

[0054] The apparatus **560** can also have a carrier assembly **590** that controls and protects the substrate **110** during planarization. The carrier assembly **590** can include a substrate holder **592** to pick up, hold and release the substrate **110** at appropriate stages of the planarizing process. The carrier assembly **590** can also have a support gantry **594** carrying a drive assembly **595** that can translate along the gantry **594**. The drive assembly **595** can have an actuator **596**, a drive shaft **597** coupled to the actuator **596**, and an arm **598** projecting from the drive shaft **597**. The arm **598** carries the substrate holder **592** via a terminal shaft **599** such that the drive assembly **595** orbits the substrate holder **592** about an axis E-E (as indicated by arrow "R_1"). The terminal shaft **599** may also rotate the substrate holder **592** about its central axis F-F (as indicated by arrow "R_2").

[0055] The planarizing pad **582** and a planarizing solution **587** define a planarizing medium that mechanically and/or chemically-mechanically removes material from the surface of the substrate **110**. The planarizing pad **582** used in the apparatus **560** can be a fixed-abrasive planarizing pad in which abrasive particles are fixedly bonded to a suspension medium. Accordingly, the planarizing solution **587** can be a "clean solution" without abrasive particles because the abrasive particles are fixedly distributed across a planarizing surface **588** of the planarizing pad **582**. In other applications, the planarizing pad **582** may be a non-abrasive pad without abrasive particles, and the planarizing solution **587** can be a slurry with abrasive particles and chemicals to remove material from the substrate **110**.

[0056] To planarize the substrate **110** with the apparatus **560**, the carrier assembly **590** presses the substrate **110** against the planarizing surface **588** of the planarizing pad **582** in the presence of the planarizing solution **587**. The drive assembly **595** then orbits the substrate holder **592** about the axis E-E and optionally rotates the substrate holder **592** about the axis F-F to translate the substrate **110** across the planarizing surface **588**. As a result, the abrasive particles and/or the chemicals in the planarizing medium remove material from the surface of the substrate **110** in a chemical and/or chemical-mechanical planarization (CMP) process. Accordingly, the planarizing pad **582** can smooth the substrate **110** by removing rough features projecting from the conductive layer **111** of the substrate **110**.

[0057] In a further aspect of this embodiment, the apparatus **560** can include an electrolyte supply vessel **530** that delivers an electrolyte to the planarizing surface of the planarizing pad **582** with a conduit **537**, as described in greater detail with reference to **FIG. 10**. The apparatus **560** can further include a current supply **521** coupled to the support table **580** and/or the top-panel **581** to supply an electrical current to electrodes positioned in the support table **580** and/or the top-panel **581**. Accordingly, the apparatus **560** can electrolytically remove material from the conductive layer **111** in a manner similar to that described above with reference to **FIGS. 1-8C**.

[0058] In one aspect of an embodiment of the apparatus **560** described above with reference to **FIG. 9**, material can be sequentially removed from the conductive layer **111** of the substrate **110** first by an electrolytic process and then by a CMP process. For example, the electrolytic process can remove material from the conductive layer **111** in a manner that roughens the conductive layer **111**. After a selected period of electrolytic processing time has elapsed, the electrolytic processing operation can be halted and additional material can be removed via CMP processing. Alternatively, the electrolytic process and the CMP process can be conducted simultaneously. In either of these processing arrangements, one feature of an embodiment of the apparatus **560** described above with reference to **FIG. 9** is that the same apparatus **560** can planarize the substrate **110** via CMP and remove material from the substrate **110** via an electrolytic process. An advantage of this arrangement is that the substrate **110** need not be moved from one apparatus to another to undergo both CMP and electrolytic processing.

[0059] Another advantage of an embodiment of the apparatus **560** described above with reference to **FIG. 9** is that the processes, when used in conjunction with each other, is expected to remove material from the substrate **110** more quickly and accurately than some conventional processes. For example, as described above, the electrolytic process can remove relatively large amounts of material in a manner that roughens the microelectronic substrate **110**, and the planarizing process can remove material on a finer scale in a manner that smoothes and/or flattens the microelectronic substrate **110**.

[0060] **FIG. 10** is a partially exploded, partially schematic isometric view of a portion of the apparatus **560** described above with reference to **FIG. 9**. In one aspect of an embodiment shown in **FIG. 10**, the top-panel **581** houses a plurality of electrode pairs **570**, each of which includes a first electrode **520*a*** and a second electrode **520*b***. The first electrodes **520*a*** are coupled to a first lead **528*a*** and the second electrodes **520*b*** are coupled to a second lead **528*b***. The first and second leads **528*a*** and **528*b*** are coupled to the current source **521** (**FIG. 9**). In one aspect of this embodiment, the first electrode **520*a*** can be separated from the second electrodes **520*b*** by an electrode dielectric layer **529*a*** that includes Teflon™ or another suitable dielectric material. The electrode dielectric layer **529*a*** can accordingly control the volume and dielectric constant of the region between the first and second electrodes **520*a*** and **520*b*** to control electrical coupling between the electrodes.

[0061] The electrodes **520*a*** and **520*b*** can be electrically coupled to the microelectronic substrate **110** (**FIG. 9**) by the planarizing pad **582**. In one aspect of this embodiment, the planarizing pad **582** is saturated with an electrolyte **531** supplied by the supply conduits **537** through apertures **538** in the top-panel **581** just beneath the planarizing pad **582**. Accordingly, the electrodes **520*a*** and **520*b*** are selected to be compatible with the electrolyte **531**. In an alternate arrangement, the electrolyte **531** can be supplied to the planarizing pad **582** from above (for example, by disposing the electrolyte **531** in the planarizing liquid **587**) rather than through the top-panel **581**. Accordingly, the planarizing pad **582** can include a pad dielectric layer **529*b*** positioned between the planarizing pad **582** and the electrodes **520*a*** and **520*b***. When the pad dielectric layer **529*b*** is in place, the electrodes **520*a*** and **520*b*** are isolated from physical contact with the electrolyte **531** and can accordingly be selected from materials that are not necessarily compatible with the electrolyte **531**.

[0062] In either of the embodiments described above with reference to **FIG. 10**, the planarizing pad **582** can provide several advantages over some conventional electrolytic arrangements. For example, the planarizing pad **582** can uniformly separate the electrodes **520***a* and **520***b* from the microelectronic substrate **110** (**FIG. 9**), which can increase the uniformity with which the electrolytic process removes material from the conductive layer **111** (**FIG. 9**). The planarizing pad **582** can also have abrasive particles **589** for planarizing the microelectronic substrate **110** in the manner described above with reference to **FIG. 9**. Furthermore, the planarizing pad **582** can filter carbon or other material that erodes from the electrodes **520***a* and **520***b* to prevent the electrode material from contacting the microelectronic substrate **110**. Still further, the planarizing pad **582** can act as a sponge to retain the electrolyte **531** in close proximity to the microelectronic substrate **110**.

[0063] **FIG. 11** is a partially schematic, cross-sectional side elevational view of a rotary apparatus **660** for planarizing and/or electrolytically processing the microelectronic substrate **110** in accordance with another embodiment of the invention. In one aspect of this embodiment, the apparatus **660** has a generally circular platen or table **680**, a carrier assembly **690**, a planarizing pad **682** positioned on the table **680**, and a planarizing liquid **687** on the planarizing pad **682**. The planarizing pad **682** can be a fixed abrasive planarizing pad or, alternatively, the planarizing liquid **687** can be a slurry having a suspension of abrasive elements and the planarizing pad **682** can be a non-abrasive pad. A drive assembly **695** rotates (arrow "G") and/or reciprocates (arrow "H") the platen **680** to move the planarizing pad **682** during planarization.

[0064] The carrier assembly **690** controls and protects the microelectronic substrate **110** during planarization. The carrier assembly **690** typically has a substrate holder **692** with a pad **694** that holds the microelectronic substrate **110** via suction. A drive assembly **696** of the carrier assembly **690** typically rotates and/or translates the substrate holder **692** (arrows "I" and "J." respectively). Alternatively, the substrate holder **692** may include a weighted, free-floating disk (not shown) that slides over the planarizing pad **682**.

[0065] To planarize the microelectronic substrate **110** with the apparatus **660**, the carrier assembly **690** presses the microelectronic substrate **110** against a planarizing surface **688** of the planarizing pad **682**. The platen **680** and/or the substrate holder **692** then move relative to one another to translate the microelectronic substrate **110** across the planarizing surface **688**. As a result, the abrasive particles in the planarizing pad **682** and/or the chemicals in the planarizing liquid **687** remove material from the surface of the microelectronic substrate **110**.

[0066] The apparatus **660** can also include a current source **621** coupled with leads **628***a* and **628***b* to one or more electrode pairs **670** (one of which is shown in **FIG. 11**). The electrode pairs **670** can be integrated with the platen **680** in generally the same manner with which the electrodes **520***a* and **520***b* (**FIG. 10**) are integrated with the top panel **581** (**FIG. 10**). Alternatively, the electrode pairs **670** can be integrated with the planarizing pad **682**. In either embodiment, the electrode pairs **670** can include electrodes having shapes and configurations generally similar to any of those described above with reference to **FIGS. 3-10** to electrolytically remove conductive material from the microelectronic substrate **110**. The electrolytic process can be carried out before, during or after the CMP process, as described above with reference to **FIG. 9**.

[0067] **FIG. 12A** is a schematic circuit representation of some of the components described above with reference to **FIG. 10**. The circuit analogy can also apply to any of the arrangements described above with reference to **FIGS. 3-11**. As shown schematically in **FIG. 12A**, the current source **521** is coupled to the first electrode **520***a* and the second electrode **520***b* with leads **528***a* and **528***b* respectively. The electrodes **520***a* and **520***b* are coupled to the microelectronic substrate **110** with the electrolyte **531** in an arrangement that can be represented schematically by two sets of parallel capacitors and resistors. A third capacitor and resistor schematically indicates that the microelectronic substrate **110**"floats" relative to ground or another potential.

[0068] In one aspect of an embodiment shown in **FIG. 12A**, the current source **521** can be coupled to an amplitude modulator **522** that modulates the signal produced by the current source **521**, as is shown in **FIG. 12B**. Accordingly, the current source **521** can generate a high-frequency wave **804**, and the amplitude modulator **522** can superimpose a low-frequency wave **802** on the high-frequency wave **804**. For example, the high-frequency wave **804** can include a series of positive or negative voltage spikes contained within a square wave envelope defined by the low-frequency wave **802**. Each spike of the high-frequency wave **804** can have a relatively steep rise time slope to transfer charge through the dielectric to the electrolyte, and a more gradual fall time slope. The fall time slope can define a straight line, as indicated by high-frequency wave **804**, or a curved line, as indicated by high-frequency wave **804***a*. In other embodiments, the high-frequency wave **804** and the low-frequency wave **802** can have other shapes depending, for example, on the particular characteristics of the dielectric material and electrolyte adjacent to the electrodes **420**, the characteristics of the substrate **110**, and/or the target rate at which material is to be removed from the substrate **110**.

[0069] An advantage of this arrangement is that the high frequency signal can transmit the required electrical energy from the electrodes **520***a* and **520***b* to the microelectronic substrate **110**, while the low frequency superimposed signal can more effectively promote the electrochemical reaction between the electrolyte **531** and the conductive layer **111** of the microelectronic substrate **110**. Accordingly, any of the embodiments described above with reference to **FIGS. 3-11** can include an amplitude modulator in addition to a current source.

[0070] From the foregoing, it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.

1-70. (canceled)

71. An apparatus for removing an electrically conductive material from a microelectronic substrate, comprising:

a support member having an engaging surface to support the microelectronic substrate;

a first conductive electrode spaced apart from the support member and spaced apart from the microelectronic substrate when the microelectronic substrate is supported by the support member;

a second conductive electrode spaced apart from the support member and the first conductive electrode, at least one of the first and second electrodes being coupleable to a source of varying current; and

an electrolyte flow restrictor positioned between the support member and at least one of the conductive electrodes to at least partially restrict a flow of an electrolyte toward at least one of the first and second electrodes.

72. The apparatus of claim 71, further comprising:

a first electrolyte adjacent to the at least one of the electrodes and selected from sodium chloride, potassium chloride and copper sulfate; and

a second electrolyte adjacent to the microelectronic substrate and selected to include hydrochloric acid.

73. The apparatus of claim 71 wherein the flow restrictor includes a permeable membrane.

74-81. (canceled)

82. The apparatus of claim 71, further comprising a vessel positioned between the support member and the at least one of the conductive electrodes, the vessel carrying the flow restrictor.

83. The apparatus of claim 82, further comprising:

a first electrolyte disposed in the vessel and adjacent to the at least one of the electrodes; and

a second electrolyte disposed outside of the vessel and adjacent to the microelectronic substrate, wherein the vessel is positioned between the first and second electrolytes.

84. The apparatus of claim 83 wherein the flow restrictor is configured to allow the first electrolyte but not the second electrolyte to pass through the flow restrictor.

85. The apparatus of claim 82 wherein the vessel is a first vessel, and wherein the apparatus further includes a second vessel positioned between the support member and the second conductive electrode, the second vessel containing a third electrolyte adjacent to the second electrode.

86. The apparatus of claim 85 wherein the flow restrictor is a first flow restrictor, and wherein the second vessel further includes a second flow restrictor between the support member and the second electrode, the second flow restrictor is configured to allow the third electrolyte but not the second electrolyte to pass through the second flow restrictor.

87. An apparatus for removing conductive material from a microelectronic substrate, comprising:

first and second electrodes spaced apart from each other and from the microelectronic substrate, at least one of the first and second electrodes being coupled to a source of varying current;

a first electrolyte adjacent to the first electrode;

a second electrolyte different from the first electrolyte adjacent to the conductive material of the microelectronic substrate; and

a flow restrictor between the first and second electrolytes and configured to at least partially restricting motion of the second electrolyte toward the first electrode.

88. The apparatus of claim 87 wherein the flow restrictor includes a permeable membrane between the first electrode and the microelectronic substrate, the membrane is configured to allow the first electrolyte but not the second electrolyte to pass through the membrane.

89. The apparatus of claim 87, wherein the first electrolyte includes a material selected from the group consisting of sodium chloride, potassium chloride, and copper sulfate.

90. The apparatus of claim 87, wherein the second electrolyte includes hydrochloric acid.

91. The apparatus of claim 87, wherein the flow restrictor includes a vessel constructed from a material selected from a group consisting of Teflon, glass, quartz, and sapphire, the vessel carrying the flow restrictor.

92. The apparatus of claim 91, further comprising a first electrolyte source in fluid communication with the vessel.

93. The apparatus of claim 87, wherein the flow restrictor is a first flow restrictor and the vessel is a first vessel, the apparatus further includes a third electrolyte adjacent to the second electrode and a second vessel carrying a second flow restrictor between the third electrolyte and the second electrolyte, the third electrolyte being different than the second electrolyte.

94. The apparatus of claim 93, wherein the second flow restrictor includes a permeable membrane between the second electrode and the microelectronic substrate, the membrane is configured to allow the third electrolyte but not the second electrolyte to pass through the membrane.

95. The apparatus of claim 94, wherein the third electrolyte is different than the first electrolyte.

96. The apparatus of claim 93, wherein the first and third electrolytes are the same.

97. The apparatus of claim 96, wherein the first electrolyte source is in fluid communication with the second vessel.

98. An apparatus for removing an electrically conductive material from a microelectronic substrate, comprising:

first and second electrodes spaced apart from each other and from the microelectronic substrate, the first and second electrodes being in electrical communication with a source of varying current;

a first electrolyte adjacent to at least one of the first and second electrodes;

a second electrolyte different than the first electrolyte adjacent to the conductive material of the microelectronic substrate; and

means for allowing the first electrolyte to flow away from the at least one of the first and second electrodes toward the conductive material but not allowing the second electrolyte to flow toward the first electrode.

99. The apparatus of claim 98, further comprising means for supplying the first electrolyte to the means for allowing the first electrolyte to flow away from the at least one of the first and second electrodes.

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