US 20160040293A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2016/0040293 A1**

Wainwright et al. (43) **Pub. Date: Feb. 11, 2016**

(54) **METHOD FOR ROLL-TO-ROLL ELECTROLESS PLATING WITH LOW DISSOLVED OXYGEN CONTENT**

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(21) Appl. No.: **14/455,227**

(22) Filed: **Aug. 8, 2014**

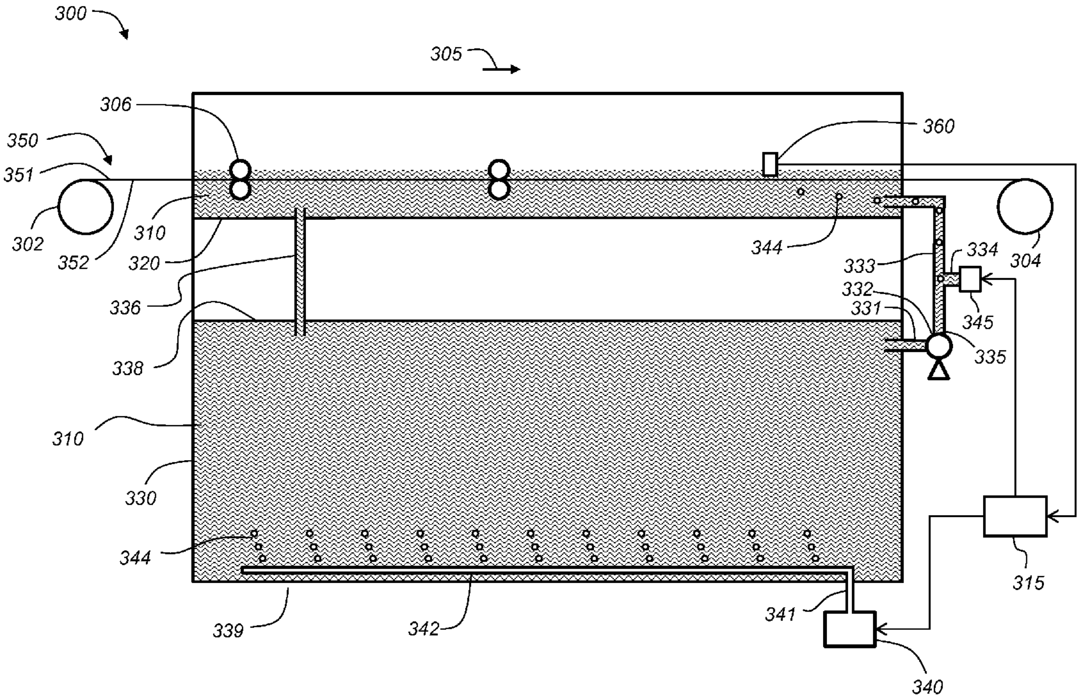
Publication Classification

(51) **Int. Cl.**
C23C 18/16 (2006.01)

(52) **U.S. Cl.**
CPC *C23C 18/1675* (2013.01); *C23C 18/163* (2013.01); *C23C 18/1617* (2013.01)

(57) **ABSTRACT**

A method of electrolessly plating a web of media, including advancing the web of media from an input roll through a pan of plating solution to a take-up roll, wherein a plating substance in the plating solution is plated onto predetermined locations on a surface of the web of media. The plating solution is circulated from a sump to the pan and back to the sump through enclosed pipes, such that plating solution in the enclosed pipes is not exposed to air. An amount of dissolved oxygen in the plating solution is measured, and an inert gas is injected into the plating solution at a rate that is controlled according to the measured amount of dissolved oxygen.



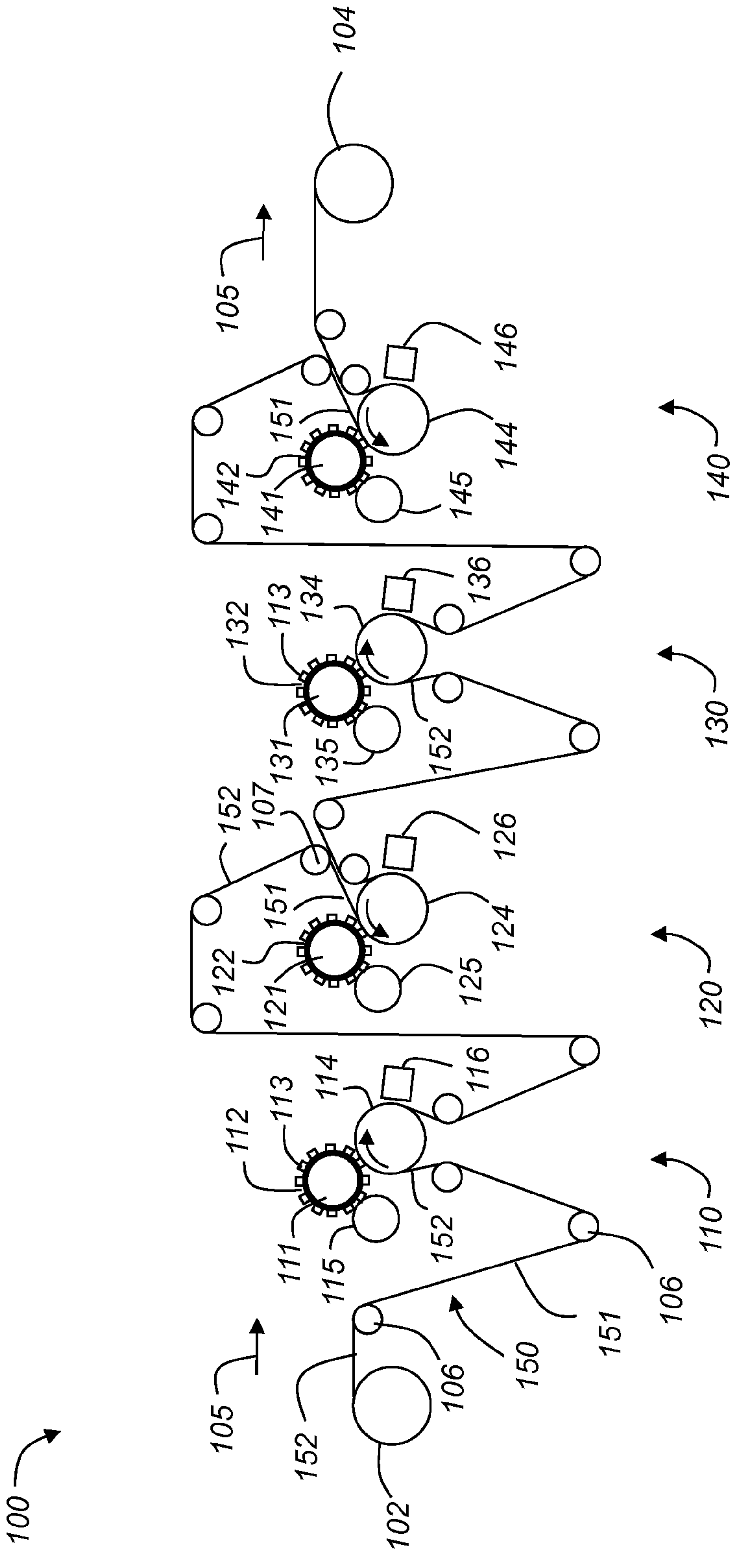

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FIG. 1

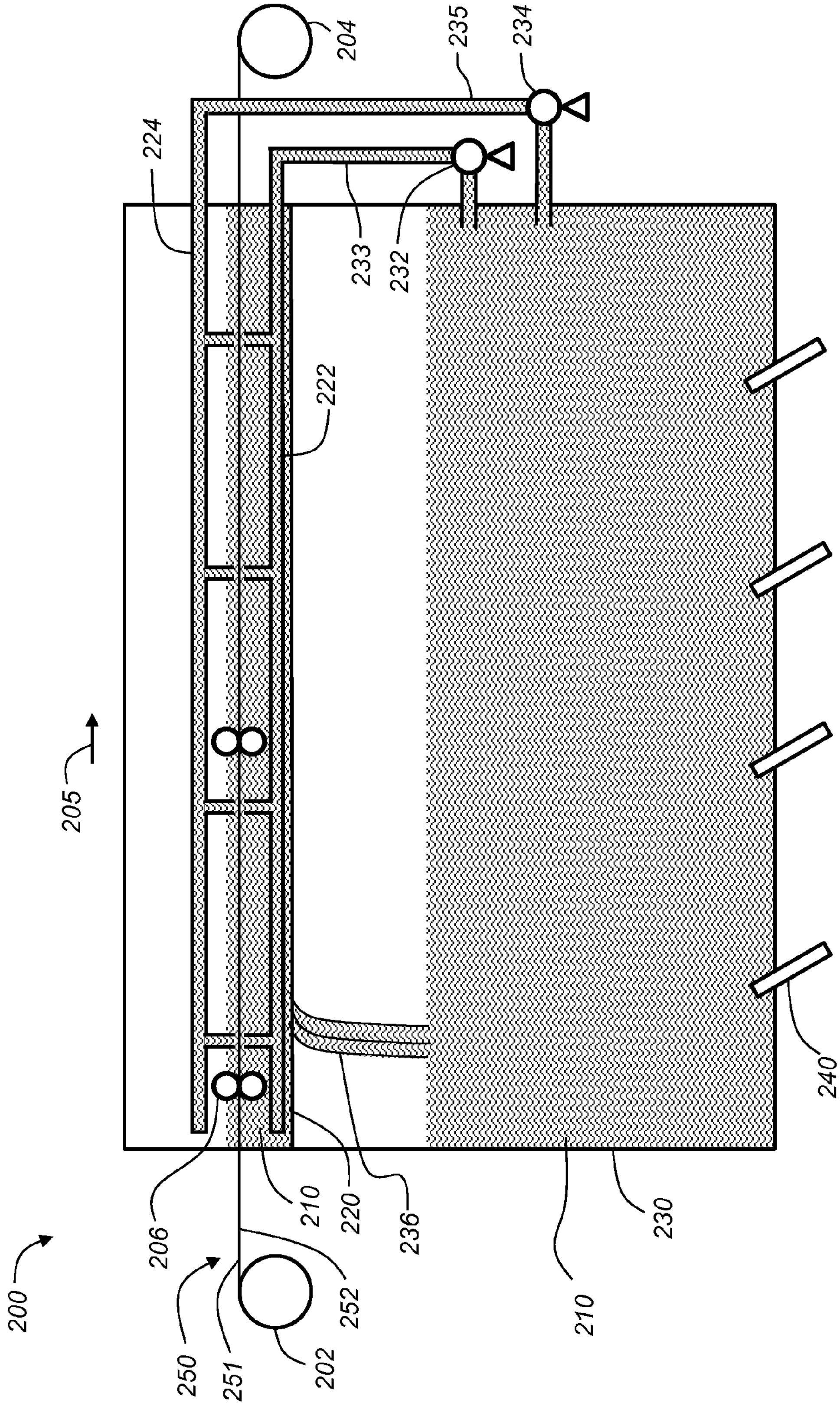

FIG. 2 (Prior Art)

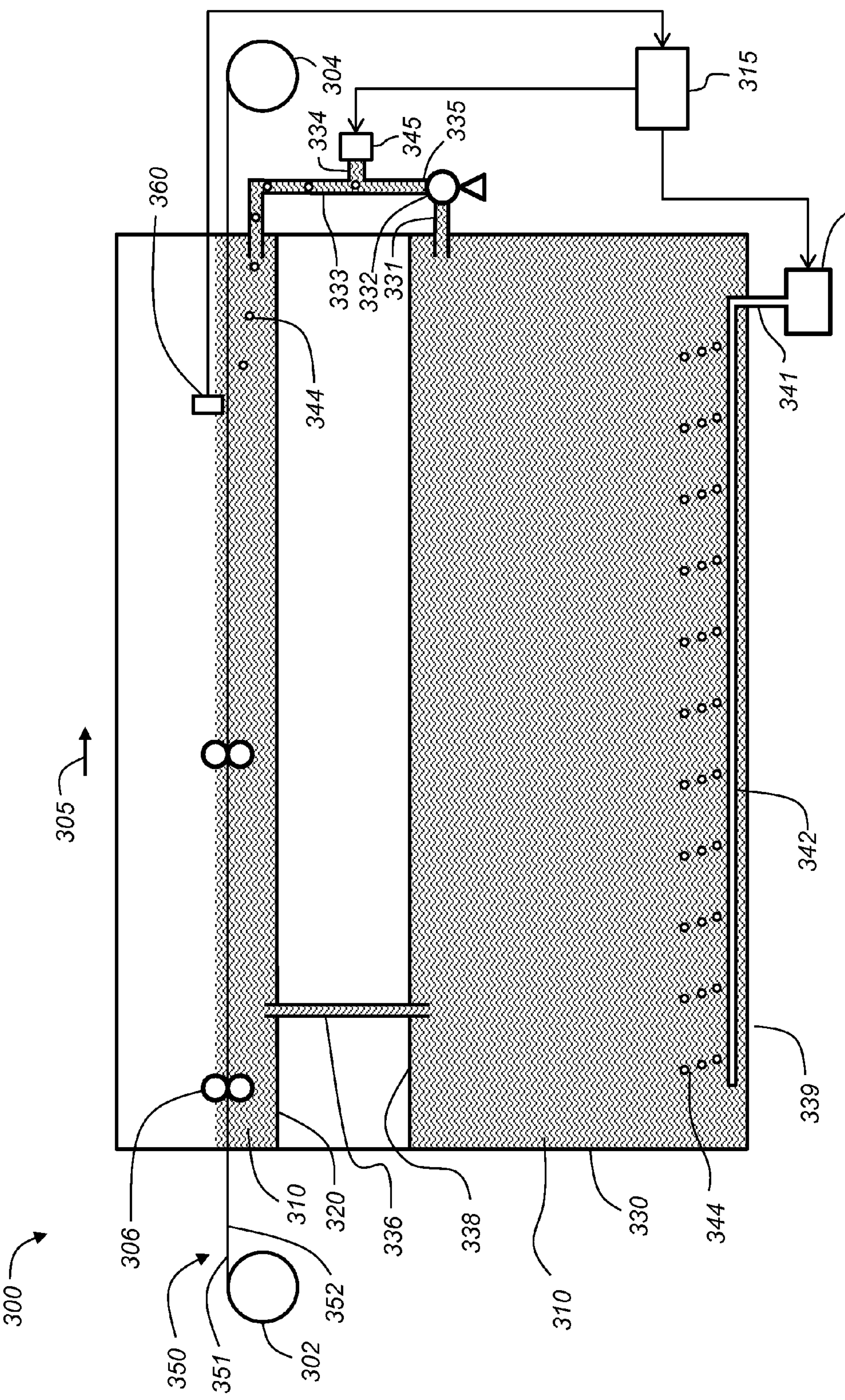
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FIG. 3

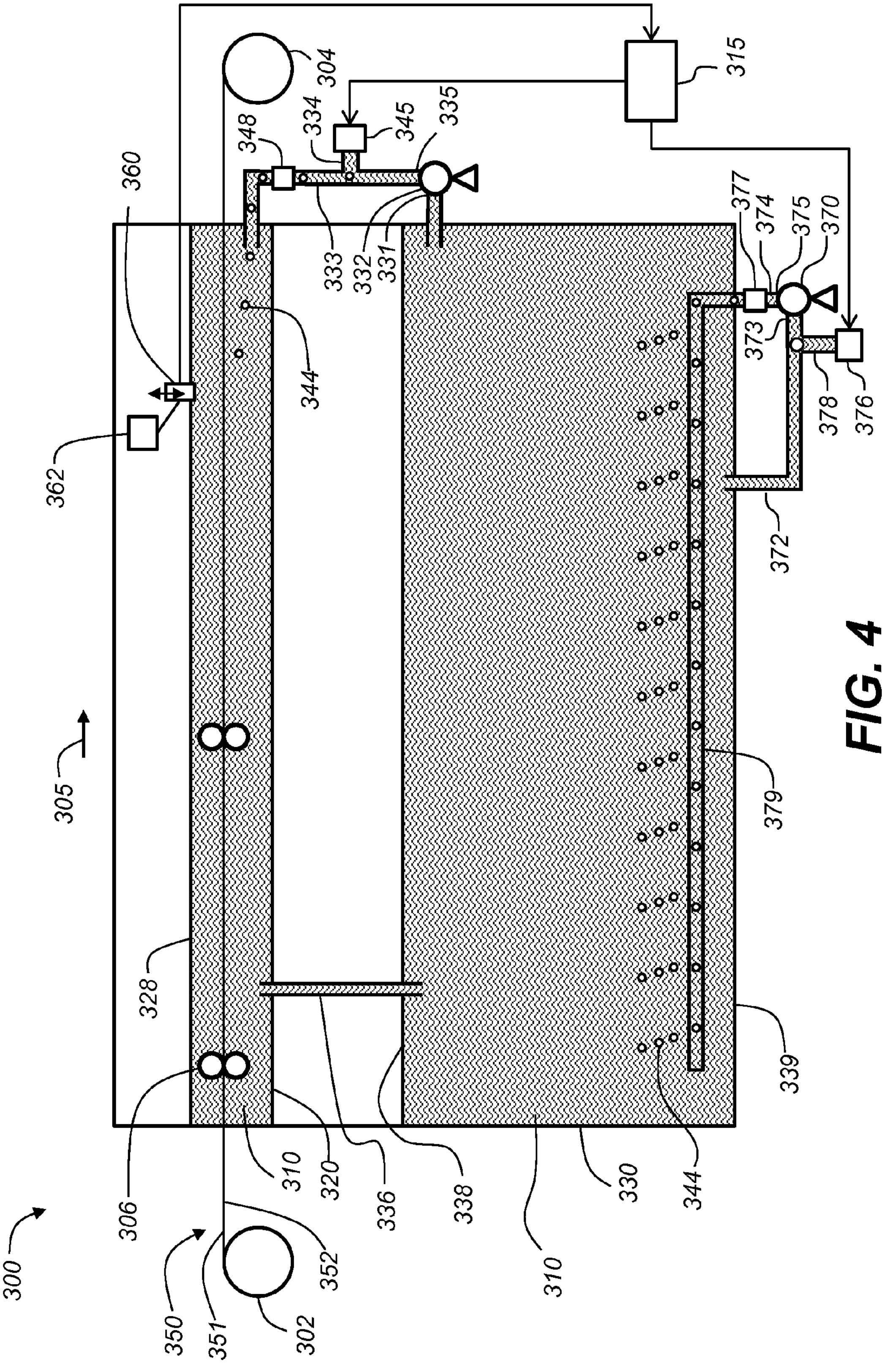
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FIG. 4

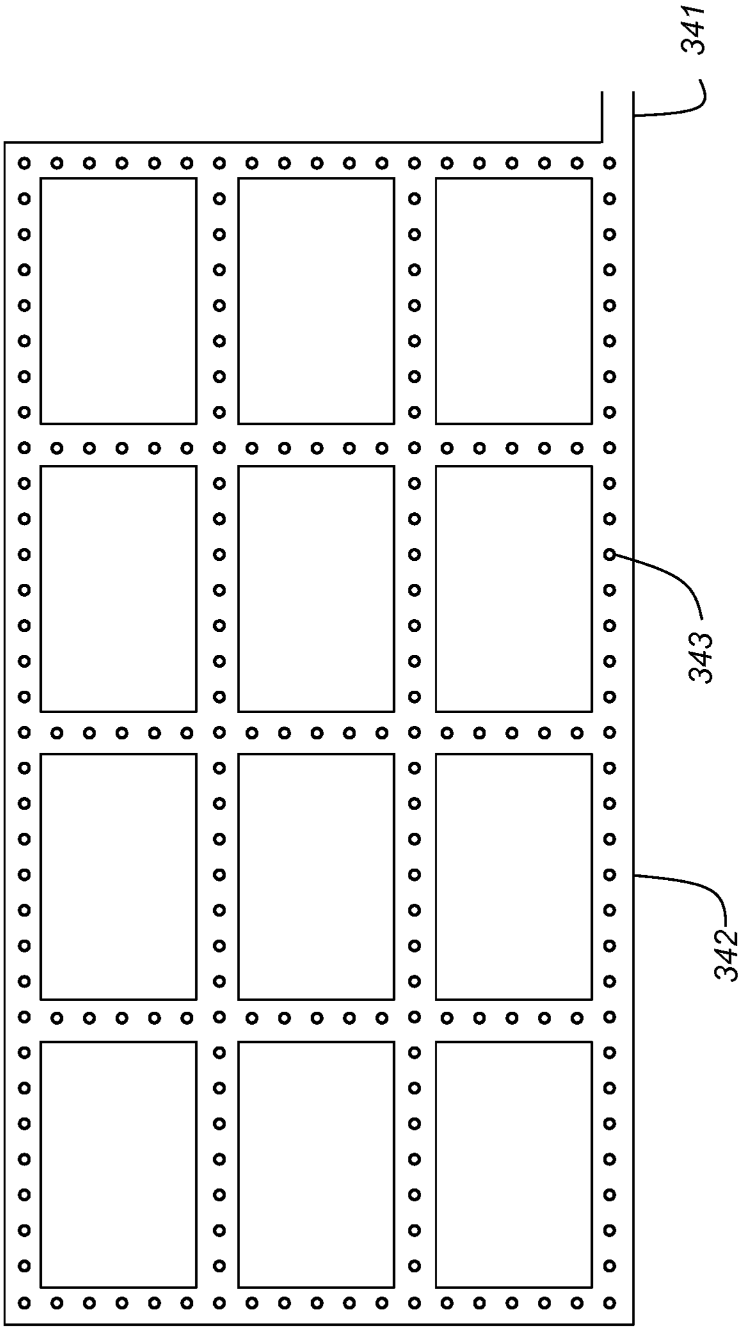

FIG. 5A

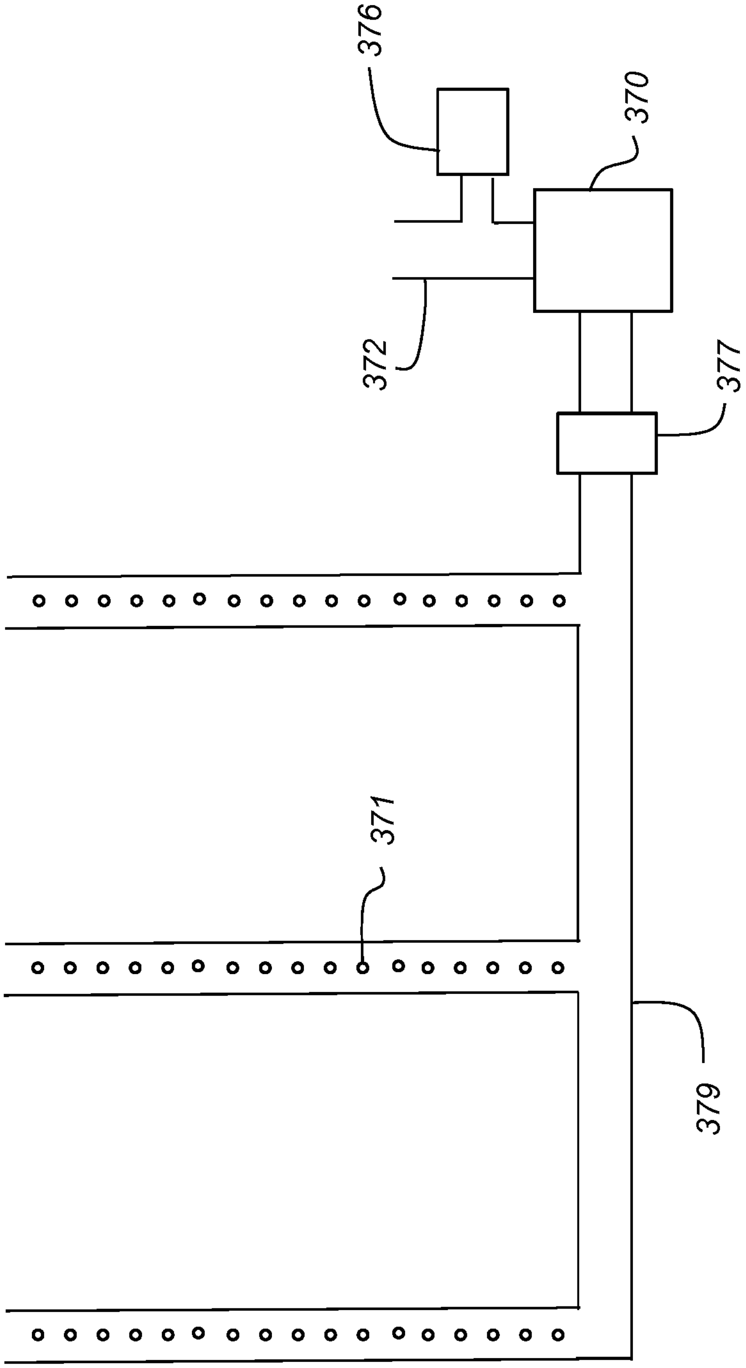

FIG. 5B

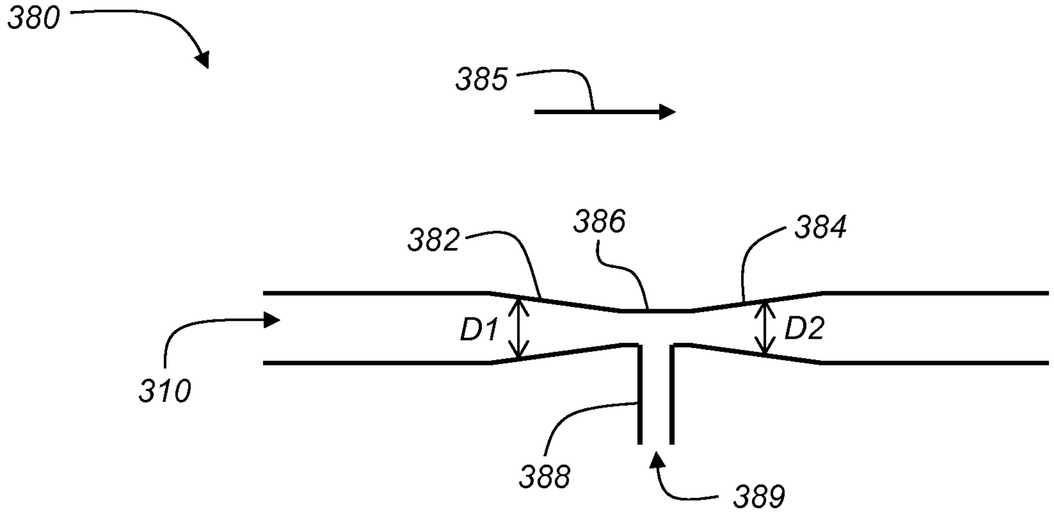

FIG. 6

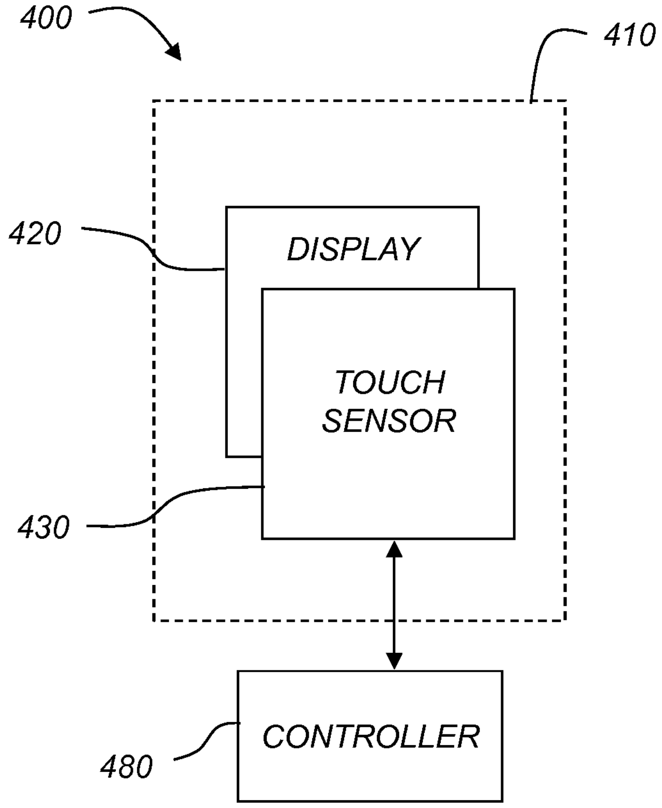

FIG. 7

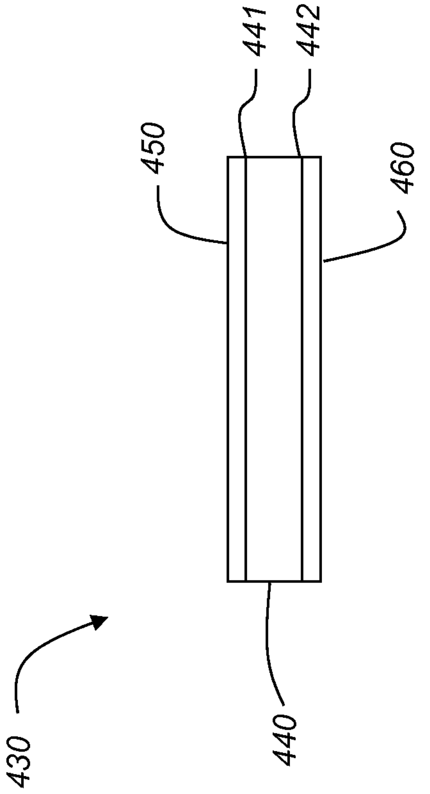

FIG. 8

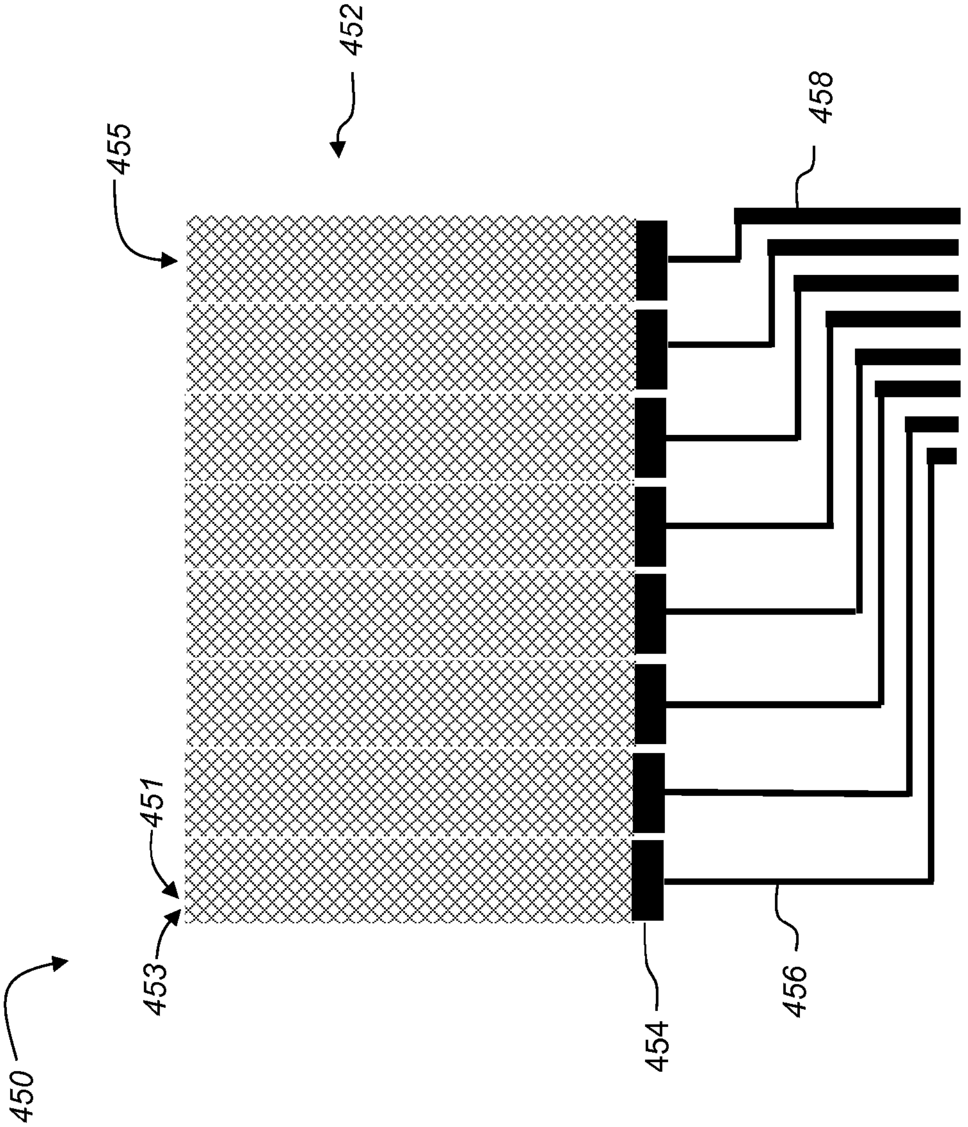

FIG. 9

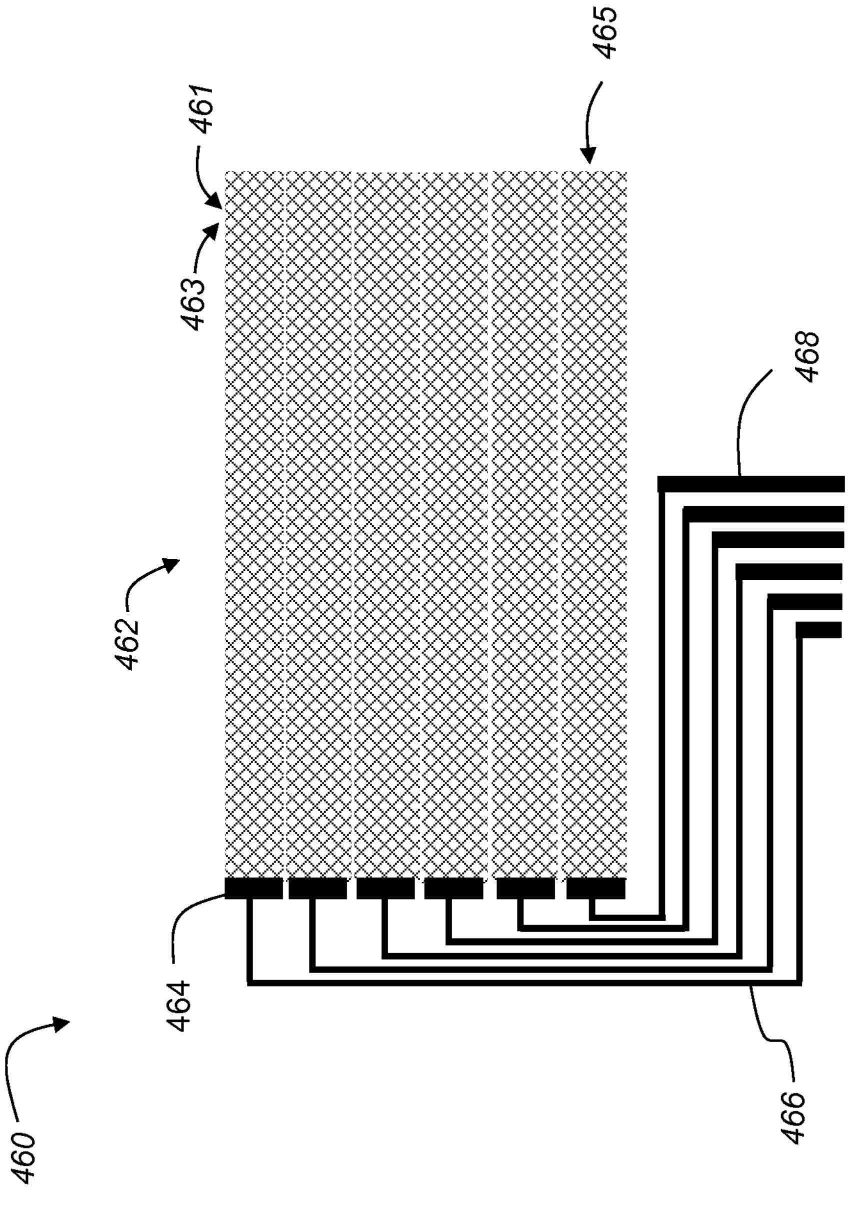

FIG. 10

METHOD FOR ROLL-TO-ROLL ELECTROLESS PLATING WITH LOW DISSOLVED OXYGEN CONTENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Reference is made to commonly-assigned, co-pending U.S. patent application Ser. No. ______ (Docket K001833), entitled "Roll-to-roll electroless plating system with low dissolved oxygen content" by G. Wainwright et al.; and to commonly-assigned, co-pending U.S. patent application Ser. No. ______ (Docket K001837), entitled "Roll-to-roll electroless plating system with micro-bubble injector" by G. Wainwright et al., each of which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This invention pertains to the field of roll-to-roll electroless plating, and more particularly to a system and method for providing low dissolved oxygen content in the plating solution.

BACKGROUND OF THE INVENTION

[0003] Electroless plating, also known as chemical or autocatalytic plating, is a non-galvanic plating process that involves chemical reactions in an aqueous plating solution that occur without the use of external electrical power. Typically, the plating occurs as hydrogen is released by a reducing agent and oxidized, thus producing a negative charge on the surface of the part to be plated. The negative charge attracts metal ions out of the plating solution to adhere as a metalized layer on the surface. Using electroless plating to provide metallization in predetermined locations can be facilitated by first depositing a catalytic material in the predetermined locations. This can be done, for example by printing features using an ink containing a catalytic component.

[0004] Touch screens are visual displays with areas that may be configured to detect both the presence and location of a touch by, for example, a finger, a hand or a stylus. Touch screens may be found in televisions, computers, computer peripherals, mobile computing devices, automobiles, appliances and game consoles, as well as in other industrial, commercial and household applications. A capacitive touch screen includes a substantially transparent substrate which is provided with electrically conductive patterns that do not excessively impair the transparency—either because the conductors are made of a material, such as indium tin oxide, that is substantially transparent, or because the conductors are sufficiently narrow that the transparency is provided by the comparatively large open areas not containing conductors. For capacitive touch screens having metallic conductors, it is advantageous for the features to be highly conductive but also very narrow. Capacitive touch screen sensor films are an example of an article having very fine features with improved electrical conductivity resulting from an electroless plated metal layer.

[0005] Projected capacitive touch technology is a variant of capacitive touch technology. Projected capacitive touch screens are made up of a matrix of rows and columns of conductive material that form a grid. Voltage applied to this grid creates a uniform electrostatic field, which can be measured. When a conductive object, such as a finger, comes into contact, it distorts the local electrostatic field at that point. This is measurable as a change in capacitance. The capacitance can be measured at every intersection point on the grid. In this way, the system is able to accurately track touches. Projected capacitive touch screens can use either mutual capacitive sensors or self capacitive sensors. In mutual capacitive sensors, there is a capacitor at every intersection of each row and each column. A 16×14 array, for example, would have 224 independent capacitors. A voltage is applied to the rows or columns. Bringing a finger or conductive stylus close to the surface of the sensor changes the local electrostatic field which reduces the mutual capacitance. The capacitance change at every individual point on the grid can be measured to accurately determine the touch location by measuring the voltage in the other axis. Mutual capacitance allows multi-touch operation where multiple fingers, palms or styli can be accurately tracked at the same time.

[0006] WO 2013/063188 by Petcavich et al. discloses a method of manufacturing a capacitive touch sensor using a roll-to-roll process to print a conductor pattern on a flexible transparent dielectric substrate. A first conductor pattern is printed on a first side of the dielectric substrate using a first flexographic printing plate and is then cured. A second conductor pattern is printed on a second side of the dielectric substrate using a second flexographic printing plate and is then cured. The ink used to print the patterns includes a catalyst that acts as seed layer during subsequent electroless plating. The electrolessly plated material (e.g., copper) provides the low resistivity in the narrow lines of the grid needed for excellent performance of the capacitive touch sensor. Petcavich et al. indicate that the line width of the flexographically printed material can be 1 to 50 microns.

[0007] Flexography is a method of printing or pattern formation that is commonly used for high-volume printing runs. It is typically employed in a roll-to-roll format for printing on a variety of soft or easily deformed materials including, but not limited to, paper, paperboard stock, corrugated board, polymeric films, fabrics, metal foils, glass, glass-coated materials, flexible glass materials and laminates of multiple materials. Coarse surfaces and stretchable polymeric films are also economically printed using flexography.

[0008] Flexographic printing members are sometimes known as relief printing members, relief-containing printing plates, printing sleeves, or printing cylinders, and are provided with raised relief images onto which ink is applied for application to a printable material. While the raised relief images are inked, the recessed relief "floor" should remain free of ink.

[0009] Although flexographic printing has conventionally been used in the past for printing of images, more recent uses of flexographic printing have included functional printing of devices, such as touch screen sensor films, antennas, and other devices to be used in electronics or other industries. Such devices typically include electrically conductive patterns.

[0010] To improve the optical quality and reliability of the touch screen, it has been found to be preferable that the width of the grid lines be approximately 2 to 10 microns, and even more preferably to be 4 to 8 microns. In addition, in order to be compatible with the high-volume roll-to-roll manufacturing process, it is preferable for the roll of flexographically printed material to be electroless plated in a roll-to-roll electroless plating system. More conventionally, electroless plating is performed by immersing the item to be plated in a tank of plating solution. However, for high volume uniform plating of features on both sides of the web of substrate material, it is preferable to perform the electroless plating in a roll-to-roll electroless plating system.

[0011] Roll-to-roll electroless plating systems are commercially available from Chemcut Corporation, for example. However, commercially available roll-to-roll electroless plating systems are adapted to be used with plating solutions that include a relatively high amount of dissolved oxygen, for example greater than three parts per million. Such plating solutions can work well for plating copper in the context of printed circuit board manufacture where the minimum line width is on the order of 100 microns. However, it has been found that such oxygen-rich plating solutions do not provide uniform metallization at high yield on features having line widths of 10 microns or less.

[0012] Dissolved oxygen content of an electroless plating solution influences the rate and quality of the plating. As indicated in U.S. Pat. No. 4,616,596 Helber Jr. et al., entitled "Electroless plating apparatus," U.S. Pat. No. 4,684,545 to Fey et al., entitled "Electroless plating with bi-level control of dissolved oxygen," and U.S. Patent Application Publication No. 2011/0214608 to Ivanov et al., entitled "Electroless Plating System," increased oxygen content tends to stabilize plating and decrease the plating rate. Decreased oxygen content tends to increase plating activity.

[0013] It has been found that a copper electroless plating solution made by Enthone is well-suited to provide high quality plating on features having minimum line widths of 10 microns or less in a low dissolved oxygen content tank plating system, but not in a commercially available roll-to-roll electroless plating system. What is needed is a roll-to-roll plating system and method that can provide and maintain low dissolved oxygen content in the plating solution.

SUMMARY OF THE INVENTION

[0014] The present invention represents a method of electrolessly plating a web of media, the method comprising:

- **[0015]** advancing the web of media from an input roll through a pan of plating solution to a take-up roll, wherein a plating substance in the plating solution is plated onto predetermined locations on a surface of the web of media as it is advanced through the plating solution in the pan;
- **[0016]** circulating the plating solution from a sump to the pan and back to the sump through enclosed pipes, such that plating solution in the enclosed pipes is not exposed to air;
- **[0017]** measuring an amount of dissolved oxygen in the plating solution; and
- **[0018]** injecting an inert gas into the plating solution at a rate that is controlled according to the measured amount of dissolved oxygen.

[0019] This invention has the advantage that the amount of dissolved oxygen can be controlled to be in a range which is optimal for use with a particular plating solution.

[0020] It has the additional advantage that low levels of dissolved oxygen can be provided appropriate for use with plating solutions whose performance degrades at higher levels of dissolved oxygen.

[0021] It has the further advantage that the exposure of the plating solution to air is minimized, thereby further reducing the amount of dissolved oxygen.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIG. **1** is a schematic side view of a flexographic printing system for roll-to-roll printing on both sides of a substrate;

[0023] FIG. **2** is a schematic side view of a prior art roll-to-roll electroless plating system;

[0024] FIG. **3** is a schematic side view of a roll-to-roll electroless plating system according to an embodiment of the invention;

[0025] FIG. **4** is a schematic side view of a roll-to-roll electroless plating system according to another embodiment of the invention;

[0026] FIG. **5**A is a top view of an exemplary embodiment of a plumbing assembly for distributing inert gas bubbles into the plating solution;

[0027] FIG. **5**B is a top view of another exemplary embodiment of a plumbing assembly for distributing inert gas bubbles into the plating solution;

[0028] FIG. **6** is a side view of an injector for injecting inert gas at a localized low pressure region;

[0029] FIG. **7** is a high-level system diagram for an apparatus having a touch screen with a touch sensor that can be printed using embodiments of the invention;

[0030] FIG. **8** is a side view of the touch sensor of FIG. **7**;

[0031] FIG. **9** is a top view of a conductive pattern printed on a first side of the touch sensor of FIG. **8**; and

[0032] FIG. **10** is a top view of a conductive pattern printed on a second side of the touch sensor of FIG. **8**.

[0033] It is to be understood that the attached drawings are for purposes of illustrating the concepts of the invention and may not be to scale.

DETAILED DESCRIPTION OF THE INVENTION

[0034] The present description will be directed in particular to elements forming part of, or cooperating more directly with, an apparatus in accordance with the present invention. It is to be understood that elements not specifically shown, labeled, or described can take various forms well known to those skilled in the art. In the following description and drawings, identical reference numerals have been used, where possible, to designate identical elements. It is to be understood that elements and components can be referred to in singular or plural form, as appropriate, without limiting the scope of the invention.

[0035] The invention is inclusive of combinations of the embodiments described herein. References to "a particular embodiment" and the like refer to features that are present in at least one embodiment of the invention. Separate references to "an embodiment" or "particular embodiments" or the like do not necessarily refer to the same embodiment or embodiments; however, such embodiments are not mutually exclusive, unless so indicated or as are readily apparent to one of skill in the art. It should be noted that, unless otherwise explicitly noted or required by context, the word "or" is used in this disclosure in a non-exclusive sense.

[0036] The example embodiments of the present invention are illustrated schematically and not to scale for the sake of clarity. One of ordinary skill in the art will be able to readily determine the specific size and interconnections of the elements of the example embodiments of the present invention.

[0037] References to upstream and downstream herein refer to direction of flow. Web media moves along a media path in a web advance direction from upstream to downstream. Similarly, fluids flow through a fluid line in a direction from upstream to downstream.

[0038] As described herein, the example embodiments of the present invention provide a roll-to-roll electroless plating system and methods for providing and maintaining low dissolved oxygen content in the plating solution. The roll-to-roll electroless plating system is useful for metalizing printed features in sensor films incorporated into touch screens. However, many other applications are emerging for printing and electroless plating of functional devices that can be incorporated into other electronic, communications, industrial, household, packaging and product identification systems (such as RFID) in addition to touch screens. In addition, roll-to-roll electroless plating systems can be used to plate items for decorative purposes rather than electronic purposes and such applications are contemplated as well.

[0039] FIG. **1** is a schematic side view of a flexographic printing system **100** that can be used in embodiments of the invention for roll-to-roll printing of a catalytic ink on both sides of a substrate **150** for subsequent electroless plating. Substrate **150** is fed as a web from supply roll **102** to take-up roll **104** through flexographic printing system **100**. Substrate **150** has a first side **151** and a second side **152**.

[0040] The flexographic printing system **100** includes two print modules **120** and **140** that are configured to print on the first side **151** of substrate **150**, as well as two print modules **110** and **130** that are configured to print on the second side **152** of substrate **150**. The web of substrate **150** travels overall in roll-to-roll direction **105** (left to right in the example of FIG. **1**). However, various rollers **106** and **107** are used to locally change the direction of the web of substrate as needed for adjusting web tension, providing a buffer, and reversing the substrate **150** for printing on an opposite side. In particular, note that in print module **120** roller **107** serves to reverse the local direction of the web of substrate **150** so that it is moving substantially in a right-to-left direction.

[0041] Each of the print modules **110**, **120**, **130**, **140** includes some similar components including a respective plate cylinder **111**, **121**, **131**, **141**, on which is mounted a respective flexographic printing plate **112**, **122**, **132**, **142**, respectively. Each flexographic printing plate **112**, **122**, **132**, **142** has raised features **113** defining an image pattern to be printed on the substrate **150**. Each print module **110**, **120**, **130**, **140** also includes a respective impression cylinder **114**, **124**, **134**, **144** that is configured to force a side of the substrate **150** into contact with the corresponding flexographic printing plate **112**, **122**, **132**, **142**. Impression cylinders **124** and **144** of print modules **120** and **140** (for printing on first side **151** of substrate **150**) rotate counter-clockwise in the view shown in FIG. **1**, while impression cylinders **114** and **134** of print modules **110** and **130** (for printing on second side **152** of substrate **150**) rotate clockwise in this view.

[0042] Each print module **110**, **120**, **130**, **140** also includes a respective anilox roller **115**, **125**, **135**, **145** for providing ink to the corresponding flexographic printing plate **112**, **122**, **132**, **142**. As is well known in the printing industry, an anilox roller is a hard cylinder, usually constructed of a steel or aluminum core, having an outer surface containing millions of very fine dimples, known as cells. Ink is provided to the anilox roller by a tray or chambered reservoir (not shown). In some embodiments, some or all of the print modules **110**, **120**, **130**, **140** also include respective UV curing stations **116**, **126**, **136**, **146** for curing the printed ink on substrate **150**.

[0043] FIG. **2** is a schematic side view of a prior art roll-to-roll electroless plating system **200**, similar to a configuration available from Chemcut Corporation, for use with a plating solution **210**. The roll-to-roll electroless plating system **200** performs well with plating solutions **210** that are formulated for optimized plating with relatively high dissolved oxygen content (e.g., greater than 3 parts per million). Substrate **250** is fed as a web of media from supply roll **202** to take-up roll **204**. Drive rollers **206** advance the web in a web advance direction **205** from the supply roll **202** through a reservoir of the plating solution **210** to the take-up roll **204**. In the configuration shown in FIG. **2**, a sump **230** contains a large volume of the plating solution **210**, and a pan **220** positioned above the sump contains a smaller volume of the plating solution **210**.

[0044] As the substrate **250** is advanced through the plating solution **210** in the pan **220**, a metallic plating substance such as copper, silver, nickel or palladium is electrolessly plated from the plating solution **210** onto predetermined locations on one or both of a first surface **251** and a second surface **252** of the substrate **250**. As a result, the concentration of the metal in the plating solution **210** in the pan **220** decreases and the plating solution **210** needs to be refreshed. To refresh the plating solution **210**, it is recirculated between the sump **230** and the pan **220**. A lower lift pump **232** moves plating solution **210** from the sump **230** through a pipe **233** to a lower flood bar **222** for distribution into the pan **220** below the substrate **250**. Likewise, an upper lift pump **234** moves plating solution **210** from the sump **230** through a pipe **235** to an upper flood bar **224** for distribution into the pan **220** above the substrate **250**. Excess plating solution **210** waterfalls back into the sump **230** at freefall return **236**. Occasionally the plating solution **210** is chemically analyzed, for example by titration, and fresh plating solution **210**, or components of the plating solution **210**, are added to the sump **230** as needed. Air inlet tubes **240** are provided to provide additional oxygen to the plating solution **210** in sump **230** as needed.

[0045] Although the prior art roll-to-roll electroless plating system **200** shown in FIG. **2** works well for plating solutions **210** that are designed to plate at relatively high levels of dissolved oxygen, for example greater than 3 parts per million, it has been found that it does not work well for plating solutions **210** that are designed to plate at a lower level of dissolved oxygen, for example between about 0.5 parts per million and about 2 parts per million. Not adding air through the air inlet tubes **240** is an obvious measure for reducing the dissolved oxygen content in the plating solution **210**. However, in order to control the dissolved oxygen content at the desired low level, it is necessary to make significant modifications to the roll-to-roll electroless plating system **200**.

[0046] FIG. **3** is a schematic side view of an improved roll-to-roll electroless plating system **300** which is useful for plating solutions **310** having a low level of dissolved oxygen content. As in the prior art electroless plating system **200**, a substrate **350** is fed as a web of media from a supply roll **302** to a take-up roll **304**. Drive rollers **306** advance the web of substrate **350** along a web advance direction **305** from the supply roll **302** through a reservoir of plating solution **310** to the take-up roll **304**. A sump **330** contains a large volume of the plating solution **310** and a pan **320** positioned above the sump contains a smaller volume of the plating solution **310**. The term "reservoir" can be used to refer to either the sump **330** or the pan **320**.

[0047] As the substrate **350** is advanced through the plating solution **310** in pan **320**, a metallic plating substance such as copper, silver, nickel or palladium is electrolessly plated from the plating solution **310** onto predetermined locations on one or both of a first surface **351** and a second surface **352** of the substrate **350**. The predetermined locations can be provided, for example, by the prior printing of a catalytic ink.

[0048] A number of modifications have been made relative to the prior art similar to a configuration available from roll-to-roll electroless plating system **200** of FIG. **2** to control the amount of dissolved oxygen in the plating solution within a lower range of about 0.5 to about 2 parts per million. The modifications include measures to a) reduce the amount of turbulence in the plating solution **310** in portions of the roll-to-roll electroless plating system **300** that are exposed to air, b) reduce the exposure of the plating solution **310** to ambient air, c) displace dissolved oxygen from the plating solution **310**, and d) sense the amount of dissolved oxygen in the plating solution **310**.

[0049] Modifications for reducing turbulence in the roll-to-roll electroless plating system **300** of FIG. **3** relative to the prior art roll-to-roll electroless plating system **200** of FIG. **2** include replacing the freefall return **236** (FIG. **2**) with a more controlled flow of the plating solution **310** through a drain pipe **336**; eliminating the lower flood bar **222** and the upper flood bar **224** (FIG. **2**); and removing the upper lift pump **234** and its associated plumbing. Instead, in roll-to-roll electroless plating system **300**, there is only a single pan-replenishing pump **332** that moves plating solution **310** from the sump **330** to the pan **320** through a pipe **333** connected to an outlet **335** of the pan-replenishing pump **332**. Plating solution **310** enters the pan-replenishing pump **332** from sump **330** via an inlet **331**.

[0050] In addition to reducing splashing and other forms of turbulence, drain pipe **336** also reduces the exposure of plating solution **310** to ambient air. The top of drain pipe **336** is within the plating solution **310** in pan **320**, and the bottom of drain pipe **336** is within the plating solution **310** in sump **330**. Other measures for reducing the exposure of plating solution **310** to ambient air include providing a sump cover **338** and optionally providing a pan cover **328** (see FIG. **4**).

[0051] Preferred embodiments of the invention also include modifications that provide for the displacement of dissolved oxygen from the plating solution **310**. This is done by injecting an inert gas into the plating solution **310** via a distribution system. As used herein, the term inert gas refers to a gas that does not take part in the chemical reactions necessary for electroless plating. Nitrogen is an example of such an inert gas. Another example of an inert gas would be argon. In various embodiments, the inert gas can also be injected into one or both of the sump **330** and pan **320**. FIG. **3** shows inert gas being injected into the pan **320** from an inert gas source **345**. In the illustrated embodiment, the inert gas from the inert gas source **345** is inserted into pipe **333** at through tee **334**, forming bubbles **344** which are carried into the pan **320**.

[0052] FIG. **3** also shows bubbles **344** of inert gas being injected into the sump **330** from inert gas source **340**. As the inert gas is dissolved in the plating solution **310**, the amount of dissolved oxygen decreases. To facilitate dissolution of the inert gas, it is advantageous to inject the inert gas as micro-bubbles and to distribute the inert gas in such a way as to promote longer paths through the plating solution **310** before exiting. In the embodiment of FIG. **3**, the bubbles **344** are injected through a plumbing assembly **342** located near a bottom **339** of sump **330** so that the injected bubbles **344** will rise through nearly the entire height of the plating solution **310**. The inert gas enters the plumbing assembly **342** from the inert gas source **340** through an inert gas inlet **341**. As shown in the top view of FIG. **5**A, in an exemplary embodiment the plumbing assembly **342** has a network of distributed orifices **343**, so that the inert gas bubbles **344** enter the plating solution **310** more uniformly, thereby facilitating dissolution by avoiding forming a few regions of inert-gas-saturated plating solution **310**.

[0053] Within the context of the present invention, micro-bubbles are defined as bubbles having a diameter between about one micron (one thousandth of a millimeter) and one millimeter. Since the ratio of surface area to volume of a sphere is inversely dependent upon diameter, micro-bubbles have a larger surface area to volume ratio than larger bubbles, thereby facilitating efficient dissolution into the plating solution **310**. In addition, micro-bubbles tend to stay suspended longer in the plating solution **310** rather than rising and bursting rapidly. As described below, there are a variety of ways to inject the inert gas into the plating solution **310** in the form of micro-bubbles.

[0054] It is also advantageous to control the amount of flow of inert gas into the plating solution **310** according to a measured amount of dissolved oxygen in the plating solution **310**. An oxygen sensor **360** can be immersed into, or periodically dipped into, the plating solution **310** to measure the dissolved oxygen content. The data from the oxygen sensor **360** can be provided to a controller **315** to control the rate of flow of inert gas injected into plating solution **310** from inert gas source **340** or inert gas source **345**, for example by controlling flow rate through a needle valve (not shown).

[0055] FIG. **4** shows a schematic side view of an alternate embodiment of a roll-to-roll electroless plating system **300** that injects micro-bubbles of inert gas into the sump **330** by means of a recirculation system including a recirculation pump **370** having an inlet **373** and an outlet **375**; an inlet line **372** for moving plating solution **310** from the sump **330** to the pump inlet **373**; and an outlet line **374** for returning plating solution **310** from the pump outlet **375** to the sump **330**. In the example shown in FIG. **4**, inert gas is injected into the low pressure inlet **373** of the recirculation pump **370** from an inert gas source **376** connected to inlet **373** by tee **378**. Mechanical action within recirculation pump **370** tends to break inert gas bubbles into micro-bubbles, which then flow together with plating solution **310** from the pump outlet **375** into the sump **330** through a plumbing assembly **342** located near bottom **339** of sump **330** providing the bubbles **344**. Furthermore, a filter **377** can be disposed in the outlet line **374** for removing particulates so that they do not re-enter the sump **330**. A second function of filter **377**, which may have a pore size on the order of one micron, can optionally be used to break up bubbles of inert gas into micro-bubbles. Thus, inert gas is injected into the plating solution **310** outside the sump **330** to provide an inert-gas-rich plating solution **310**, and the inert-gas-rich plating solution **310** is delivered into the sump **330**.

[0056] FIG. **5**B shows a top view of an exemplary embodiment of the plumbing assembly **379**, where the inert gas is injected from the inert gas source **376** into the inlet line **372** to the recirculation pump **370**. The inert gas bubbles pass through a filter **377** before entering plumbing assembly **379**. The bubbles of inert gas have a long flow path within plumbing assembly **379** before exiting at distributed orifices **371**, thereby aiding dissolution of the inert gas into the plating solution **310** (FIG. **4**) within the plumbing assembly **379**.

[0057] An advantage of injecting inert gas on the low pressure inlet side of a pump is that the inert gas source **376** can be a low pressure source for improved flow control. However, a potential disadvantage of injecting inert gas into a pump inlet is cavitation damage within the pump. FIG. **4** also shows inert gas flowing from inert gas source **345** through a tee **334** into pipe **333** downstream of the outlet **335** of pan-replenishing pump **332**. Thus, inert gas is injected into the plating solution **310** outside the pan **320** to provide an inert-gas-rich plating solution **310**, and the inert-gas-rich plating solution **310** is delivered into the pan **320** through the pipe **333**. A filter **348** can be used for further reducing the size of bubbles.

[0058] In some embodiments, a static mixer (not shown) having a tortuous flow path around baffles can be inserted in-line with pipe **333** to facilitate dissolution of the inert gas micro-bubbles within the plating solution **310** being returned to pan **320** through pipe **333**.

[0059] Although FIG. **4** shows inert gas provided upstream of the inlet **373** of recirculation pump **370**, and shows inert gas provided downstream of the outlet **335** of pan-replenishing pump **332**, alternatively inert gas could be provide downstream of outlet **375** of recirculation pump **370** or upstream of inlet **331** of pan-replenishing pump **332**.

[0060] For configurations where the inert gas is provided downstream of the outlet of a pump (i.e., on the high pressure side of the pump), it is advantageous to provide a local low pressure region where the inert gas can be injected. For example, in FIG. **4**, it can be useful to provide a local low pressure region where the inert gas is injected downstream of the outlet **335** of the pan-replenishing pump **332**. FIG. **6** is a side view of an injector **380** (sometimes called a Venturi injector) for providing a local low pressure region at a gas injection site. The injector **380** can be used at the position of the tee **334** in FIG. **4**. Injector **380** includes a throat **386**; converging tube segment **382** upstream of the throat **386** having a diameter D**1** that decreases from an upstream portion to a downstream portion; and a diverging tube segment **384** downstream of the throat **386** having a diameter D**2** that increases from an upstream portion to a downstream portion. The throat **386** is formed by the junction of the converging tube segment **382** and the diverging tube segment **384**. The plating solution **310** flows through the injector **380** from upstream to downstream in flow direction **385**. Due to the Venturi effect, a localized low pressure region is formed at the throat **386**. By providing an inlet **388** for inert gas **389** in proximity to the throat **386**, a low pressure source of inert gas, such as inert gas sources **340**, **345** (FIG. **4**) can be used. In some operating conditions it has been found that micro-bubbles tend to be formed when the inert gas is injected using injector **380**, thereby providing an additional advantage for the use of this device. In some embodiments, an injector **380** can be also be used to inject inert gas downstream of the outlet **375** of the recirculation pump **370** (FIG. **4**).

[0061] Having described exemplary embodiments of the roll-to-roll electroless plating system **300**, a context has been provided for describing further details of methods for controlling the dissolved oxygen content to be at its desired low range (e.g., in the range of about 0.5 to about 2 parts per million). As described above, an amount of dissolved oxygen in the plating solution **310** is measured using oxygen sensor **360**. The measured amount of dissolved oxygen is compared to a target range of dissolved oxygen. If the measured amount of dissolved oxygen is greater than the target range of dissolved oxygen, then the rate of injecting the inert gas is increased, for example by further opening a needle valve through which the inert gas flows to increase the flow rate. If the measured amount of dissolved oxygen is less than the target range of dissolved oxygen, then the rate of injecting the inert gas is decreased, for example by further closing a needle valve through which the inert gas flows to decrease the flow rate.

[0062] In some embodiments, the measuring of the amount of dissolved oxygen can be repeated at specified time intervals, for example once every five minutes or once every hour. During start-up of the electroless plating process, prior to injecting inert gas, the plating solution **310** tends to be somewhat oxygen rich. Therefore, it can be advantageous to measure the dissolved oxygen content at a relatively high repetition frequency (e.g., once every five minutes) during a start-up phase, and then to measure the dissolved oxygen content at a lower repetition frequency (e.g., once per thirty minutes) after the system has stabilized and the dissolved oxygen content has reached the target range.

[0063] In some embodiments, measurement of dissolved oxygen content can also be initiated by the controller **315** if it detects that an environmental condition has changed. For example, a measurement can be initiated if the controller **315** senses that the temperature of the plating solution **310** has changed by more than a predetermined threshold, as gas solubility is a function of temperature.

[0064] In some embodiments, measurement of dissolved oxygen content can also be initiated when a system operating condition changes. For example, a measurement can be initiated if the pan cover **328** is removed for service, thereby exposing the surface of the plating solution **310** to the air. Likewise, a measurement can be initiated when fresh plating solution **310**, or components of the plating solution **310**, are added to the sump **330**.

[0065] In some embodiments, measurement of dissolved oxygen content can also be initiated when an indication is detected that the system may not be performing in the intended manner. For example, a measurement can be initiated if it is observed that elements of the plating solution **310** are plating onto extraneous surfaces other than the intended features on the substrate **250**.

[0066] In some embodiments, a user interface can be provided to enable the measurement of dissolved oxygen to be manually initiated by an operator. For example, if it is observed that the system performance has been degraded.

[0067] For embodiments where the inert gas is injected into the plating solution **310** for delivery into both the sump **330** and the pan **320**, the rates of injection can be independently controlled by controller **315**. For example, the injection of the inert gas into the plating solution **310** for delivery into the sump **330** can be done at a first rate, and the injection of inert gas into the plating solution **310** for delivery into the pan **320** can be done at a second rate that is different from the first rate.

[0068] FIG. **3** shows the oxygen sensor **360** submerged within the plating solution **310** in pan **320**. In some embodiments, if the oxygen sensor **360** is kept within the plating solution **310**, metal can deposit on it, thereby affecting its performance. FIG. **4** shows an embodiment where the oxygen sensor **360** is configured to be repositionable. Under control of controller **315**, a motor **362** controllably lowers the oxygen sensor **360** to dip it into the plating solution **310** (e.g., through an opening in the pan cover **328**) in order to measure dissolved oxygen content. The controller **315** can then control the motor **362** to raise the oxygen sensor **360** to remove it from the plating solution after the measurement is made. Data indicating the measured amount of dissolved oxygen can be sent to controller **315** either before or after the oxygen sensor **360** is removed from the plating solution **310**.

[0069] FIG. **7** shows a high-level system diagram for an apparatus **400** having a touch screen **410** including a display device **420** and a touch sensor **430** that overlays at least a portion of a viewable area of display device **420**. Touch sensor **430** senses touch and conveys electrical signals (related to capacitance values for example) corresponding to the sensed touch to a controller **480**. Touch sensor **430** is an example of an article that can be printed on one or both sides by the flexographic printing system **100** and plated using an embodiment of roll-to-roll electroless plating system **300** with low dissolved oxygen content described above.

[0070] FIG. **8** shows a schematic side view of a touch sensor **430**. Transparent substrate **440**, for example polyethylene terephthalate, has a first conductive pattern **450** printed and plated on a first side **441**, and a second conductive pattern **460** printed and plated on a second side **442**. The length and width of the transparent substrate **440**, which is cut from the take-up roll **104** (FIG. **1**), is not larger than the flexographic printing plates **112**, **122**, **132**, **142** of flexographic printing system **100** (FIG. **1**), but it could be smaller than the flexographic printing plates **112**, **122**, **132**, **142**.

[0071] FIG. **9** shows an example of a conductive pattern **450** that can be printed on first side **441** (FIG. **8**) of substrate **440** (FIG. **8**) using one or more print modules such as print modules **120** and **140** of flexographic printing system (FIG. **1**), followed by plating using an embodiment of roll-to-roll electroless plating system **300** (FIGS. **3** and **4**). Conductive pattern **450** includes a grid **452** including grid columns **455** of intersecting fine lines **451** and **453** that are connected to an array of channel pads **454**. Interconnect lines **456** connect the channel pads **454** to the connector pads **458** that are connected to controller **480** (FIG. **7**). Conductive pattern **450** can be printed by a single print module **120** in some embodiments. However, because the optimal print conditions for fine lines **451** and **453** (e.g., having line widths on the order of 4 to 8 microns) are typically different than for printing the wider channel pads **454**, connector pads **458** and interconnect lines **456**, it can be advantageous to use one print module **120** for printing the fine lines **451** and **453** and a second print module **140** for printing the wider features. Furthermore, for clean intersections of fine lines **451** and **453**, it can be further advantageous to print and cure one set of fine lines **451** using one print module **120**, and to print and cure the second set of fine lines **453** using a second print module **140**, and to print the wider features using a third print module (not shown in FIG. **1**) configured similarly to print modules **120** and **140**.

[0072] FIG. **10** shows an example of a conductive pattern **460** that can be printed on second side **442** (FIG. **8**) of substrate **440** (FIG. **8**) using one or more print modules such as print modules **110** and **130** of flexographic printing system (FIG. **1**), followed by plating using an embodiment of roll-to-roll electroless plating system **300** (FIGS. **3** and **4**). Conductive pattern **460** includes a grid **462** including grid rows **465** of intersecting fine lines **461** and **463** that are connected to an array of channel pads **464**. Interconnect lines **466** connect the channel pads **464** to the connector pads **468** that are connected to controller **480** (FIG. **7**). In some embodiments, conductive pattern **460** can be printed by a single print module **110**. However, because the optimal print conditions for fine lines **461** and **463** (e.g., having line widths on the order of 4 to 8 microns) are typically different than for the wider channel pads **464**, connector pads **468** and interconnect lines **466**, it can be advantageous to use one print module **110** for printing the fine lines **461** and **463** and a second print module **130** for printing the wider features. Furthermore, for clean intersections of fine lines **461** and **463**, it can be further advantageous to print and cure one set of fine lines **461** using one print module **110**, and to print and cure the second set of fine lines **463** using a second print module **130**, and to print the wider features using a third print module (not shown in FIG. **1**) configured similarly to print modules **110** and **130**.

[0073] Alternatively, in some embodiments conductive pattern **450** can be printed using one or more print modules configured like print modules **110** and **130**, and conductive pattern **460** can be printed using one or more print modules configured like print modules **120** and **140** of FIG. **1** followed by plating using an embodiment of roll-to-roll electroless plating system **300** (FIGS. **3** and **4**).

[0074] With reference to FIGS. **7-10**, in operation of touch screen **410**, controller **480** can sequentially electrically drive grid columns **455** via connector pads **458** and can sequentially sense electrical signals on grid rows **465** via connector pads **468**. In other embodiments, the driving and sensing roles of the grid columns **455** and the grid rows **465** can be reversed.

[0075] The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

[0076] **100** flexographic printing system
[0077] **102** supply roll
[0078] **104** take-up roll
[0079] **105** roll-to-roll direction
[0080] **106** roller
[0081] **107** roller
[0082] **110** print module
[0083] **111** plate cylinder
[0084] **112** flexographic printing plate
[0085] **113** raised features
[0086] **114** impression cylinder
[0087] **115** anilox roller
[0088] **116** UV curing station
[0089] **120** print module
[0090] **121** plate cylinder
[0091] **122** flexographic printing plate
[0092] **124** impression cylinder
[0093] **125** anilox roller
[0094] **126** UV curing station
[0095] **130** print module
[0096] **131** plate cylinder
[0097] **132** flexographic printing plate
[0098] **134** impression cylinder
[0099] **135** anilox roller
[0100] **136** UV curing station
[0101] **140** print module
[0102] **141** plate cylinder
[0103] **142** flexographic printing plate
[0104] **144** impression cylinder
[0105] **145** anilox roller
[0106] **146** UV curing station
[0107] **150** substrate

[0108] **151** first side

[0109] **152** second side

[0110] **200** roll-to-roll electroless plating system

[0111] **202** supply roll

[0112] **204** take-up roll

[0113] **205** web advance direction

[0114] **206** drive roller

[0115] **210** plating solution

[0116] **220** pan

[0117] **222** lower flood bar

[0118] **224** upper flood bar

[0119] **230** sump

[0120] **232** lower lift pump

[0121] **233** pipe

[0122] **234** upper lift pump

[0123] **235** pipe

[0124] **236** freefall return

[0125] **240** air inlet tube

[0126] **250** substrate

[0127] **251** first surface

[0128] **252** second surface

[0129] **300** roll-to-roll electroless plating system

[0130] **302** supply roll

[0131] **304** take-up roll

[0132] **305** web advance direction

[0133] **306** drive roller

[0134] **310** plating solution

[0135] **315** controller

[0136] **320** pan

[0137] **328** pan cover

[0138] **330** sump

[0139] **331** inlet

[0140] **332** pan-replenishing pump

[0141] **333** pipe

[0142] **334** tee

[0143] **335** outlet

[0144] **336** drain pipe

[0145] **338** sump cover

[0146] **339** bottom

[0147] **340** inert gas source

[0148] **341** inert gas inlet

[0149] **342** plumbing assembly

[0150] **343** orifices

[0151] **344** bubbles

[0152] **345** inert gas source

[0153] **348** filter

[0154] **350** substrate

[0155] **351** first surface

[0156] **352** second surface

[0157] **360** oxygen sensor

[0158] **362** motor

[0159] **370** recirculation pump

[0160] **371** orifices

[0161] **372** inlet line

[0162] **373** inlet

[0163] **374** outlet line

[0164] **375** outlet

[0165] **376** inert gas source

[0166] **377** filter

[0167] **378** tee

[0168] **379** plumbing assembly

[0169] **380** injector

[0170] **382** converging tube segment

[0171] **384** diverging tube segment

[0172] **385** flow direction

[0173] **386** throat

[0174] **388** inlet

[0175] **389** inert gas

[0176] **400** apparatus

[0177] **410** touch screen

[0178] **420** display device

[0179] **430** touch sensor

[0180] **440** transparent substrate

[0181] **441** first side

[0182] **442** second side

[0183] **450** conductive pattern

[0184] **451** fine lines

[0185] **452** grid

[0186] **453** fine lines

[0187] **454** channel pads

[0188] **455** grid column

[0189] **456** interconnect lines

[0190] **458** connector pads

[0191] **460** conductive pattern

[0192] **461** fine lines

[0193] **462** grid

[0194] **463** fine lines

[0195] **464** channel pads

[0196] **465** grid row

[0197] **466** interconnect lines

[0198] **468** connector pads

[0199] **480** controller

[0200] D**1** diameter

[0201] D**2** diameter

1. A method of electrolessly plating a web of media, the method comprising:

advancing the web of media from an input roll through a pan of plating solution to a take-up roll, wherein a plating substance in the plating solution is plated onto predetermined locations on a surface of the web of media as it is advanced through the plating solution in the pan;

circulating the plating solution from a sump to the pan and back to the sump through enclosed pipes, such that plating solution in the enclosed pipes is not exposed to air;

measuring an amount of dissolved oxygen in the plating solution at a sequence of different measurement times separated by specified time intervals, wherein the time interval between subsequent measurement times at a first time is smaller than interval between subsequent measurement times at a later second time; and

injecting an inert gas into the plating solution at a rate that is controlled according to the measured amount of dissolved oxygen.

2. The method of claim **1**, wherein injecting the inert gas includes:

comparing the measured amount of dissolved oxygen in the plating solution to a target range of dissolved oxygen;

increasing the rate of injecting the inert gas if the measured amount of dissolved oxygen is greater than the target range of dissolved oxygen; and

decreasing the rate of injecting the inert gas if the measured amount of dissolved oxygen is less than the target range of dissolved oxygen.

3. The method of claim **2**, wherein increasing the rate of injecting the inert gas includes increasing a flow rate of the inert gas through a valve, and wherein decreasing the rate of injecting the inert gas includes decreasing the flow rate of the inert gas through the valve.

4-6. (canceled)

7. The method of claim **1**, wherein the step of measuring the amount of dissolved oxygen includes using a motor to controllably lower an oxygen sensor to dip it into the plating solution and then raise the oxygen sensor to remove it from the plating solution.

8. The method of claim **1**, wherein the step of injecting the inert gas into the plating solution includes injecting the inert gas into the plating solution outside the sump and the pan to provide an inert-gas-rich plating solution.

9. The method of claim **8**, further including delivering the inert-gas-rich plating solution into the sump.

10. The method of claim **8**, further including delivering the inert-gas-rich plating solution into the pan.

11. The method of claim **8**, further including delivering the inert-gas-rich plating solution into both the sump and the pan.

12. The method of claim **11**, wherein the inert gas injected into the plating solution for delivery into the sump is injected at a first rate, and wherein the inert gas injected into the plating solution for delivery into the pan is injected at a second rate that is different from the first rate.

13. The method of claim **8**, further including passing the inert-gas-rich plating solution through a device that produces micro-bubbles of inert-gas within the inert-gas-rich plating solution.

14. The method of claim **13**, wherein the device includes a pump having a low-pressure inlet into which the inert gas is injected.

15. The method of claim **13**, wherein the device includes a filter.

16. The method of claim **8**, wherein the inert gas is injected into the plating solution using an injector including:

a converging tube segment;

a diverging tube segment downstream of the converging tube segment;

a throat formed at a junction of the converging tube segment and the diverging tube segment; and

an inlet for the injecting the inert gas in proximity to the throat.

17. A method of electrolessly plating a web of media, the method comprising:

advancing the web of media from an input roll through a pan of plating solution to a take-up roll, wherein a plating substance in the plating solution is plated onto predetermined locations on a surface of the web of media as it is advanced through the plating solution in the pan;

circulating the plating solution from a sump to the pan and back to the sump through enclosed pipes, such that plating solution in the enclosed pipes is not exposed to air;

measuring an amount of dissolved oxygen in the plating solution; and

injecting an inert gas into the plating solution at a rate that is controlled according to the measured amount of dissolved oxygen;

wherein the step of measuring the amount of dissolved oxygen is initiated when a predefined condition is detected.

18. The method of claim **17**, wherein detecting the predefined condition includes detecting that a temperature of the plating solution changes by more than a predetermined threshold, detecting a change in a system operating condition, or detecting that the plating substance is plating onto extraneous surfaces other than the predetermined locations on the surface of the web of media.

19. A method of electrolessly plating a web of media, the method comprising:

advancing the web of media from an input roll through a pan of plating solution to a take-up roll, wherein a plating substance in the plating solution is plated onto predetermined locations on a surface of the web of media as it is advanced through the plating solution in the pan;

circulating the plating solution from a sump to the pan and back to the sump through enclosed pipes, such that plating solution in the enclosed pipes is not exposed to air;

measuring an amount of dissolved oxygen in the plating solution at a plurality of different times; and

injecting an inert gas into the plating solution at a rate that is controlled according to the measured amount of dissolved oxygen;

wherein the step of measuring the amount of dissolved oxygen at a particular time includes:

controlling a motor to lower an oxygen sensor to dip it into the plating solution;

using the oxygen sensor to measure the amount of dissolved oxygen in the plating solution; and

controlling the motor to raise the oxygen sensor to remove it from the plating solution, thereby reducing an amount of plating substance that is plated onto the oxygen sensor between subsequent measurements.

20. The method of claim **19**, wherein the pan has a pan cover, and wherein the oxygen sensor is lowered into the plating solution and raised out of the plating solution through an opening in the pan cover.

* * * * *