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(54) **SEALED SOLID STATE BATTERY**  
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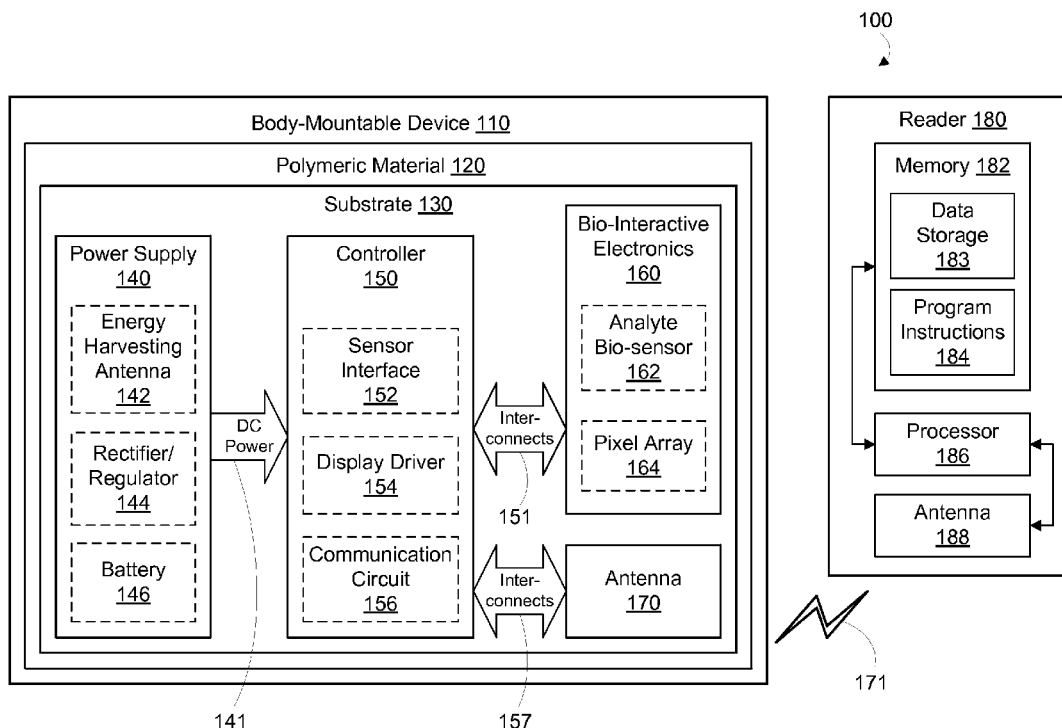
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(57) **ABSTRACT**

An electrochemical battery can include electrodes (a cathode and an electrode) arranged on respective surfaces of an electrolyte. The electrodes and electrolyte can each be solid state films that can be layered on top of one another to create a stacked structure disposed on a substrate. A polymeric sealant material can be applied over and around the battery stack and a moisture barrier can be formed over the sealant material to thereby prevent moisture from reaching the battery. Conductive terminals electrically coupled to the cathode and anode, respectively, can be formed on a second side of the substrate. As such, the battery can be flip-chip mounted to corresponding mounting pads and thereby connected to other electronics that can receive power from the battery.



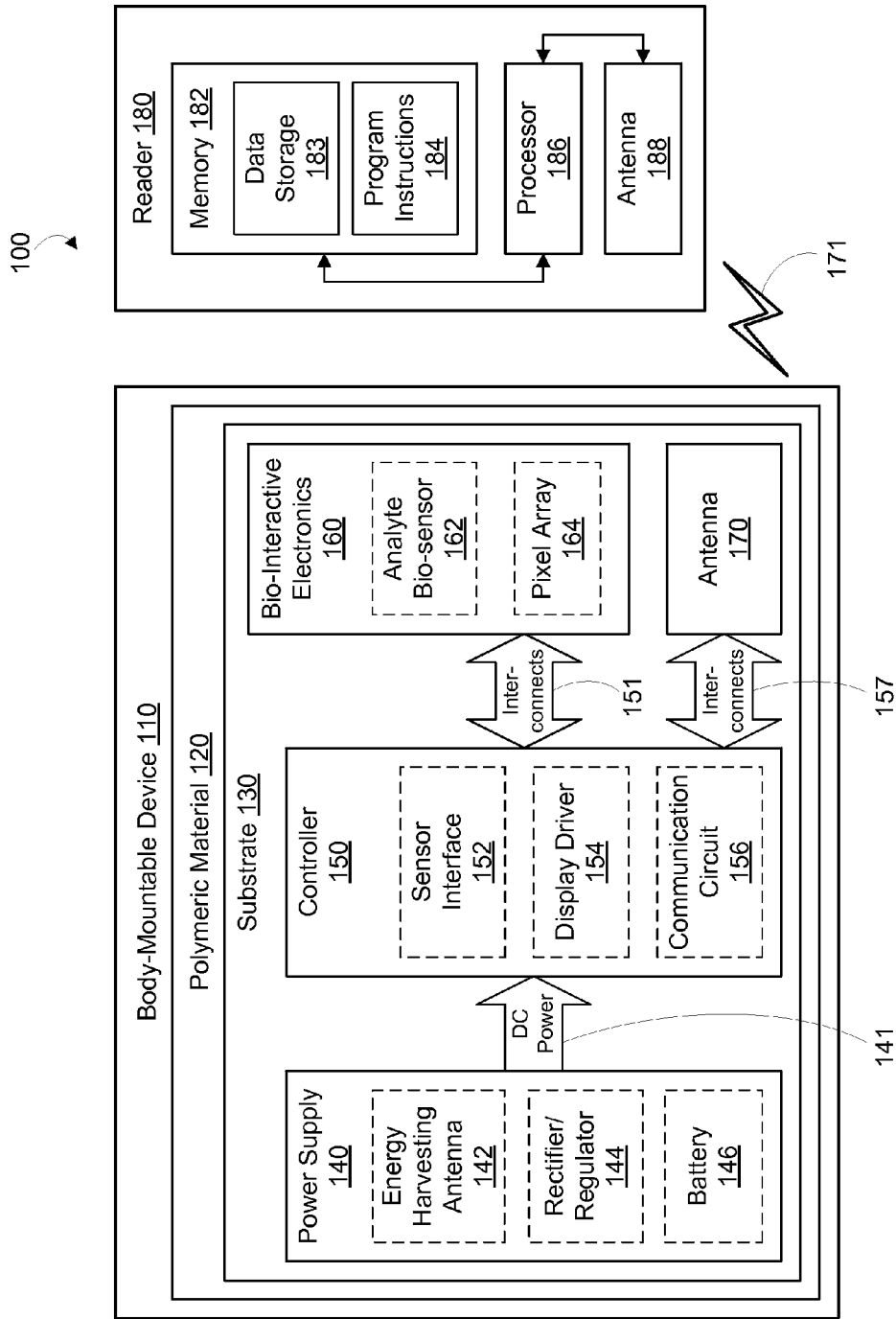
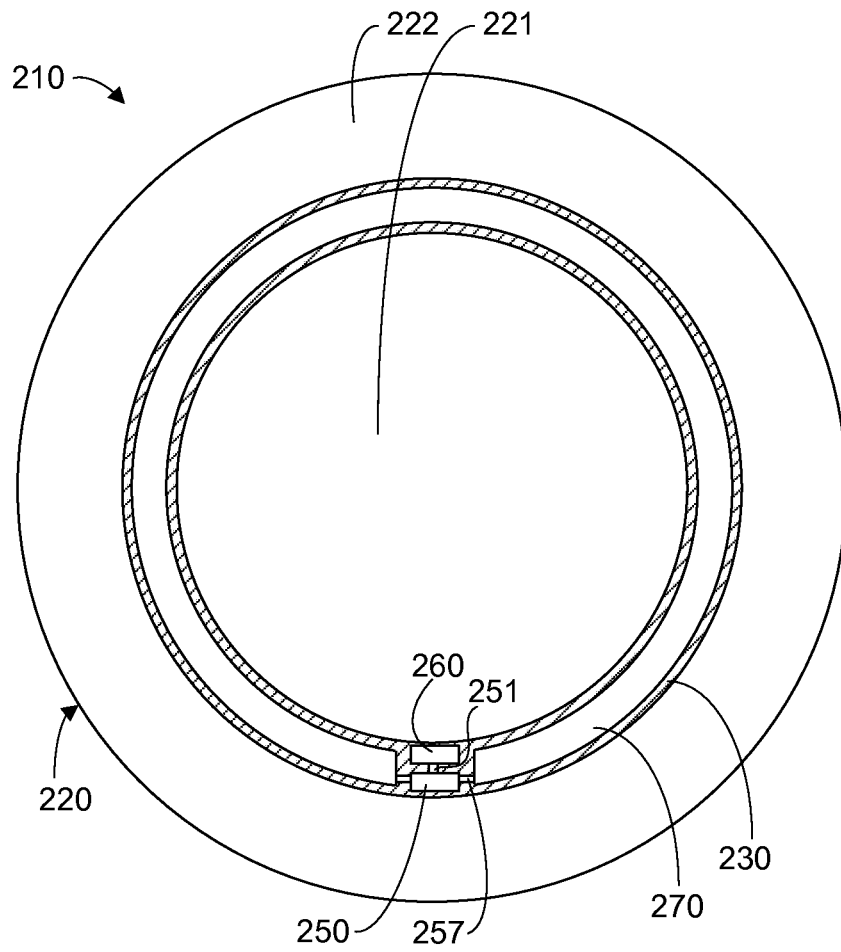
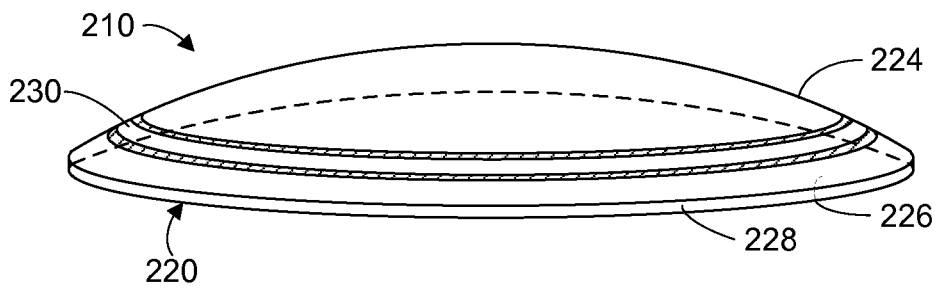


FIG. 1



**FIG. 2A**



**FIG. 2B**

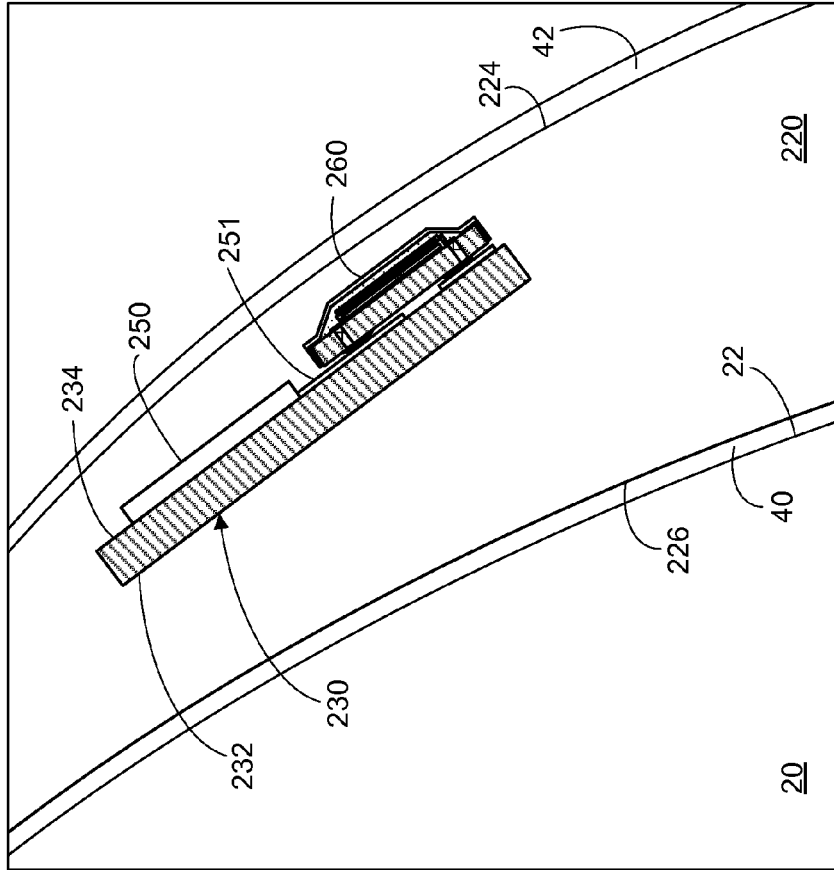


FIG. 2D

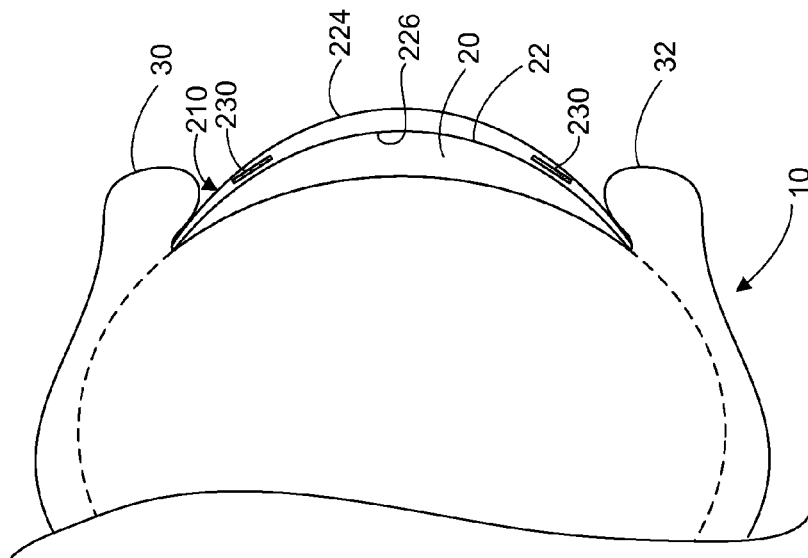
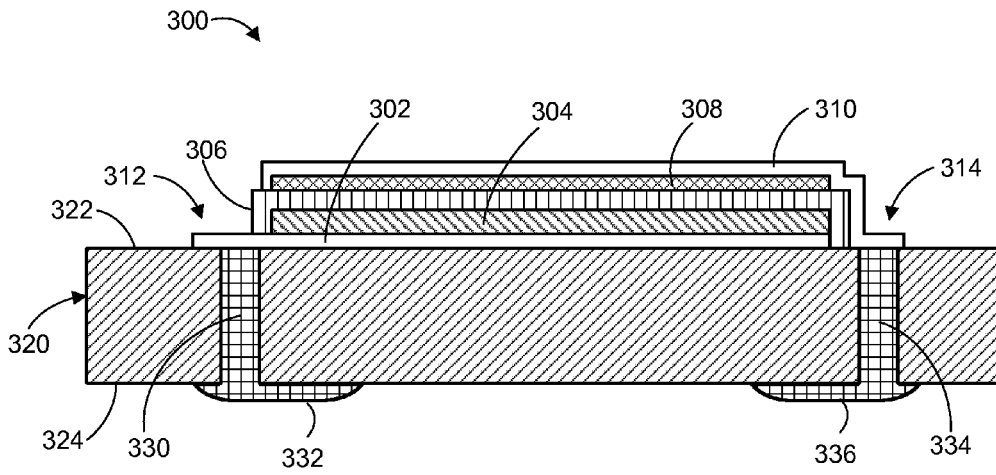
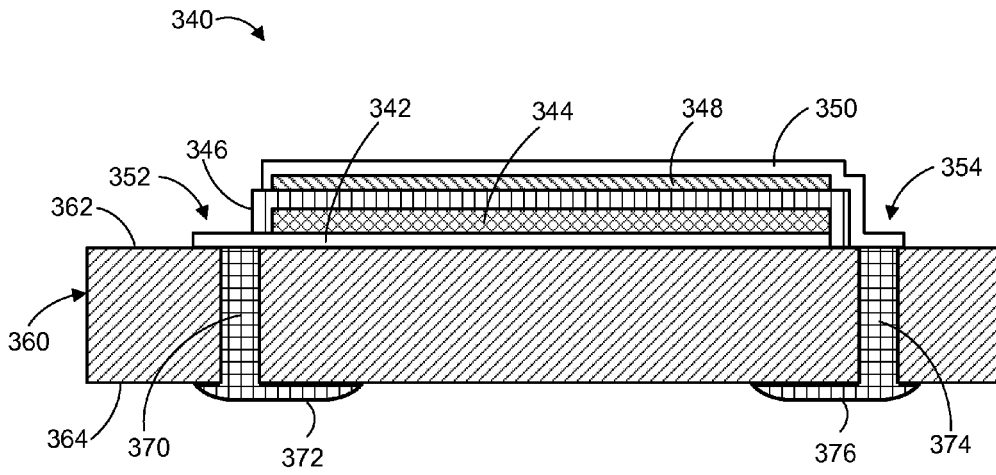


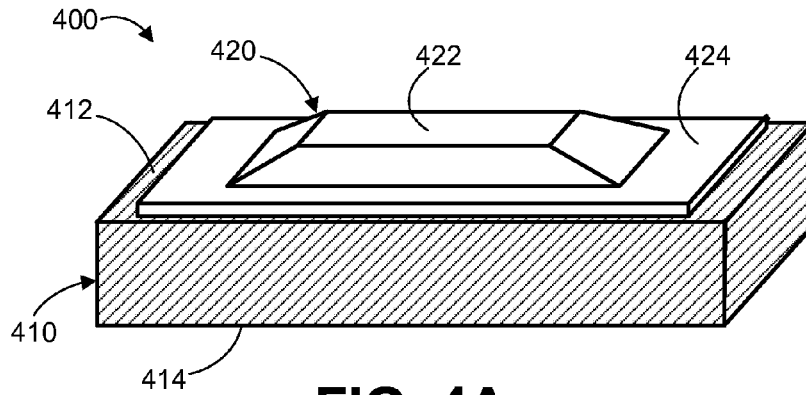
FIG. 2C



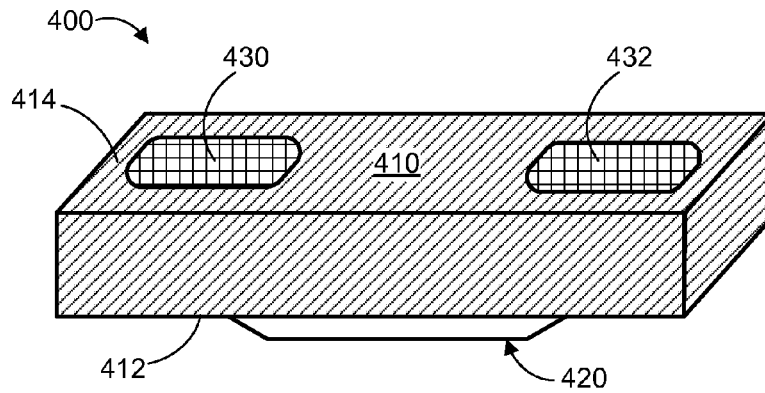
**FIG. 3A**



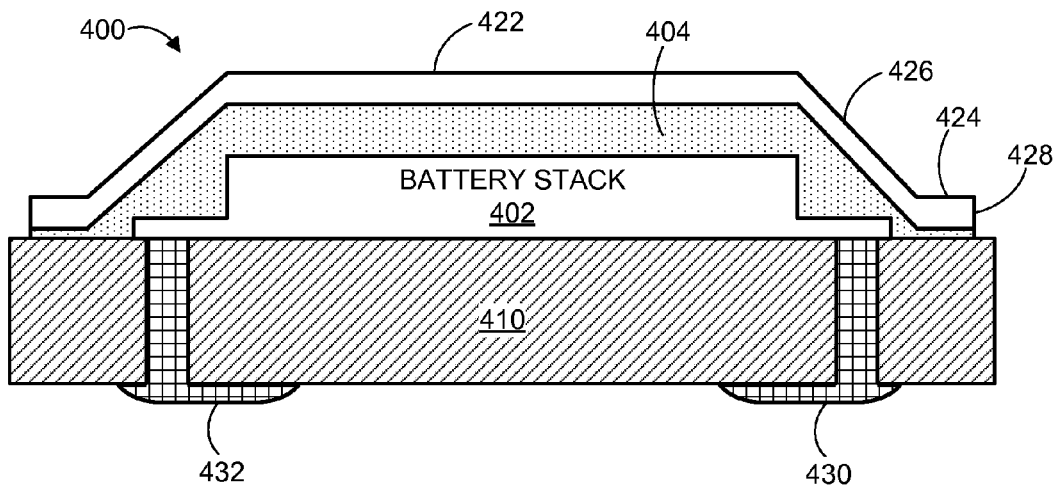
**FIG. 3B**



**FIG. 4A**



**FIG. 4B**



**FIG. 4C**

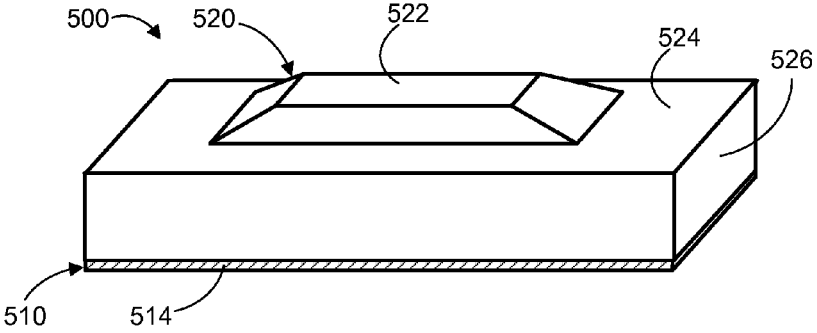


FIG. 5A

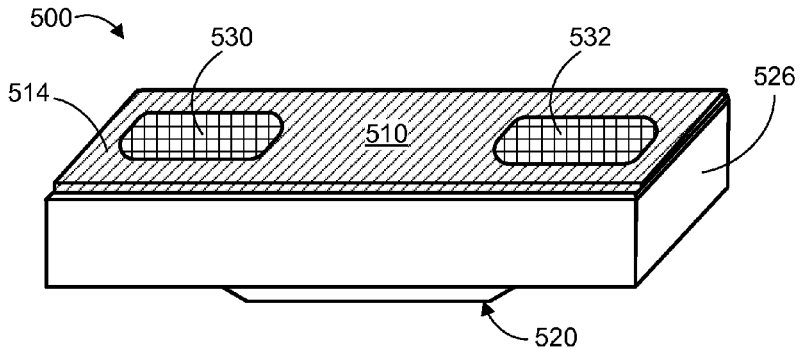


FIG. 5B

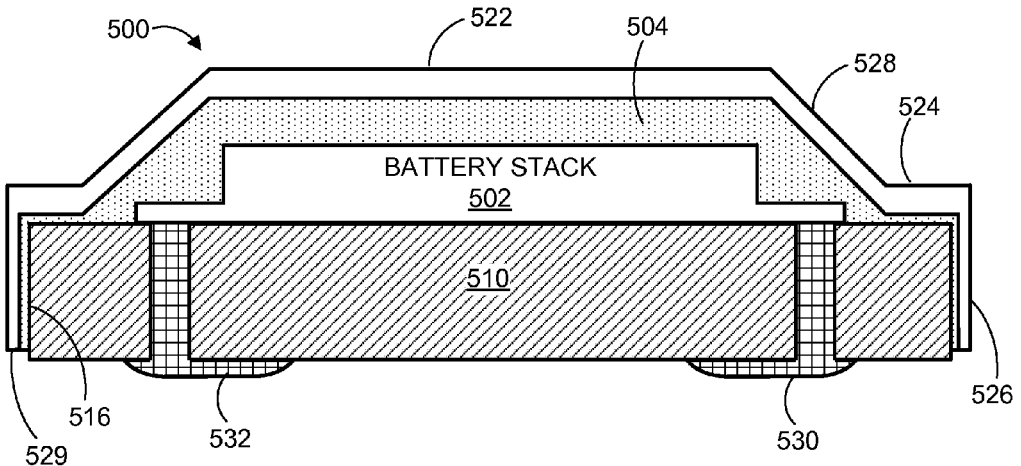


FIG. 5C

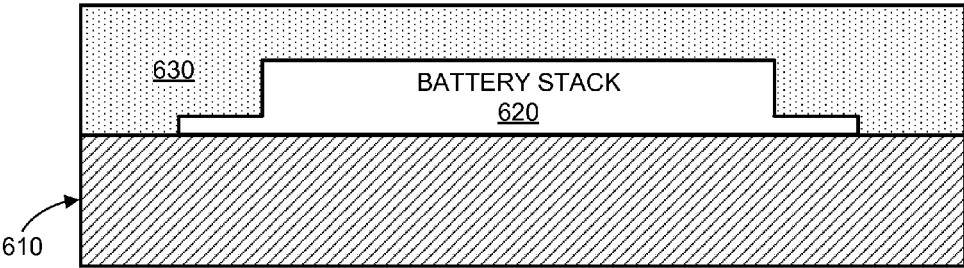


FIG. 6A

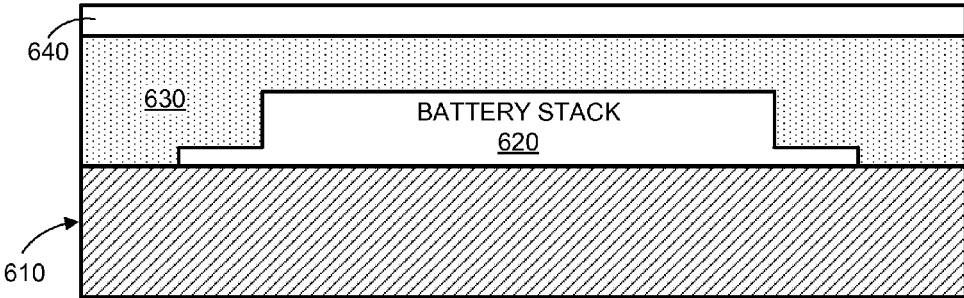


FIG. 6B

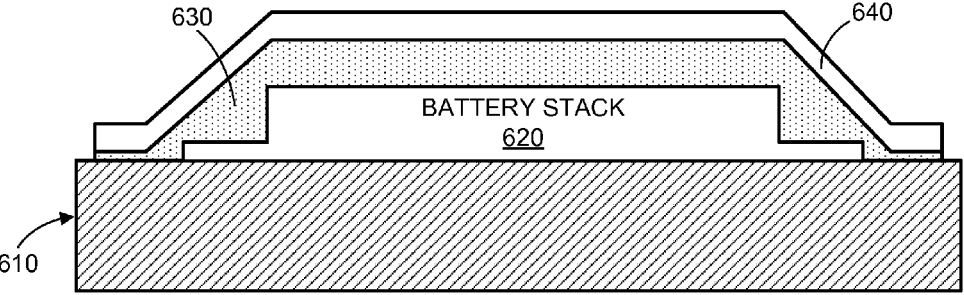
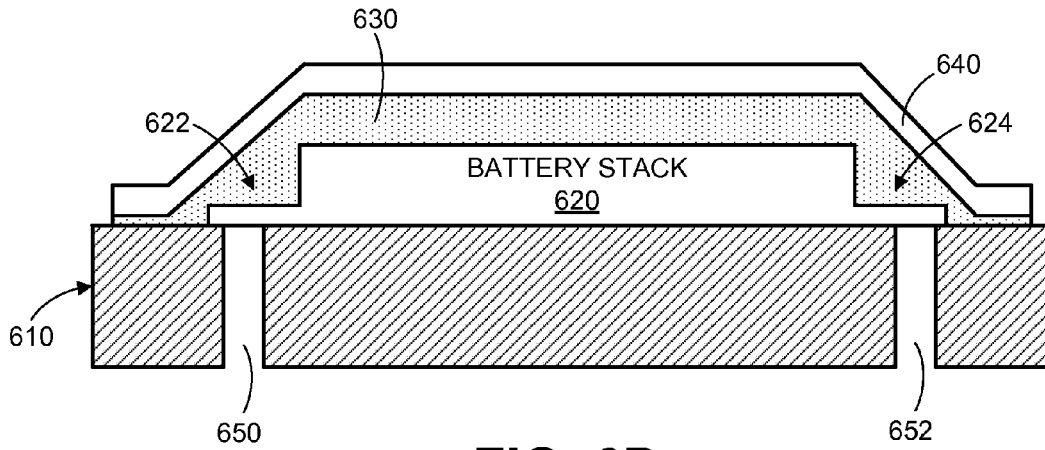
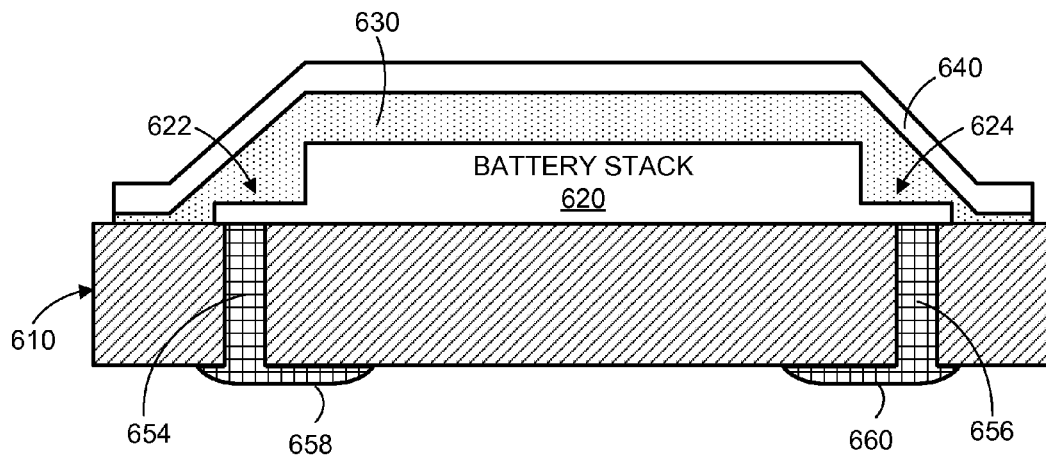


FIG. 6C

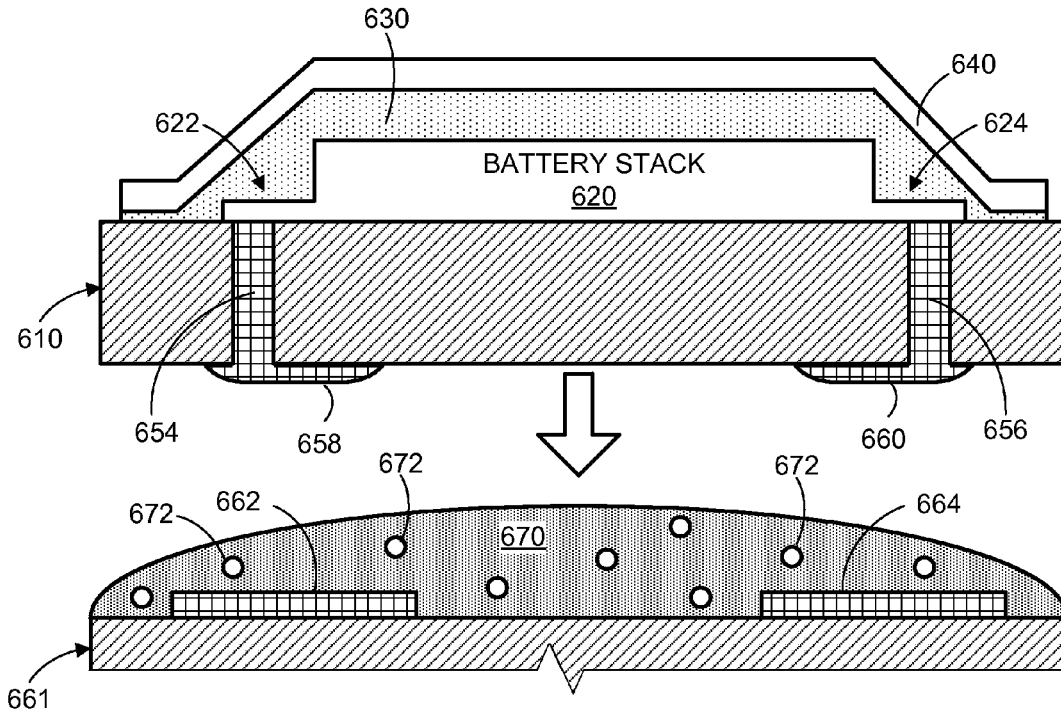




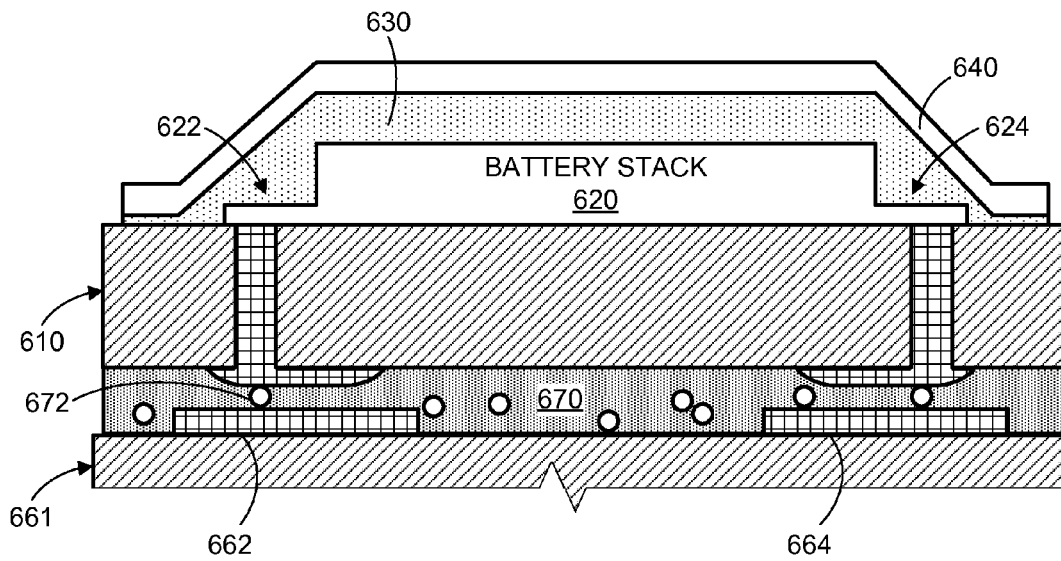
**FIG. 6D**



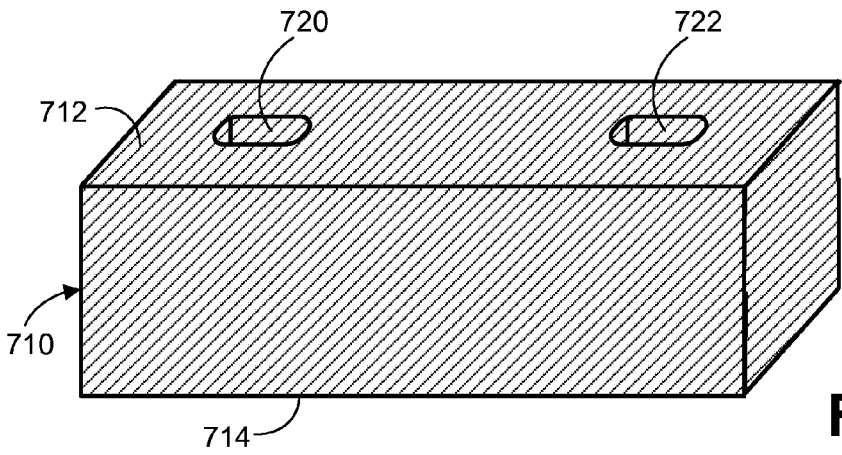
**FIG. 6E**



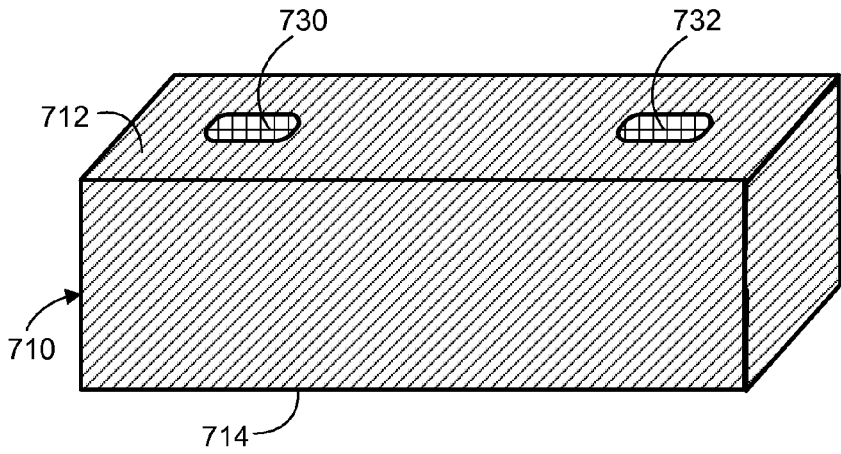
**FIG. 6F**



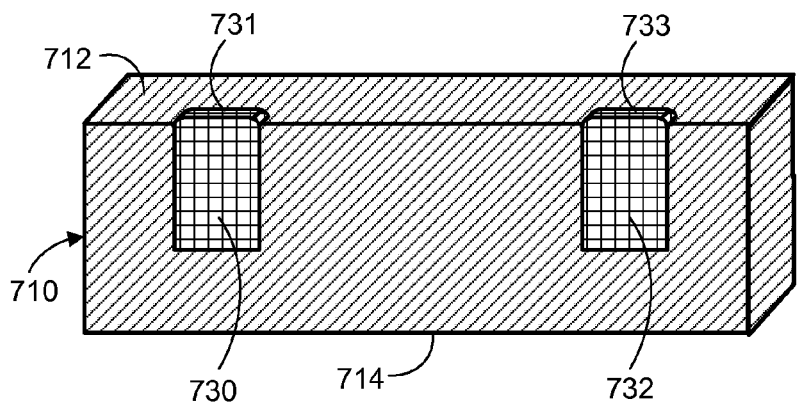
**FIG. 6G**



**FIG. 7A**



**FIG. 7B**



**FIG. 7C**

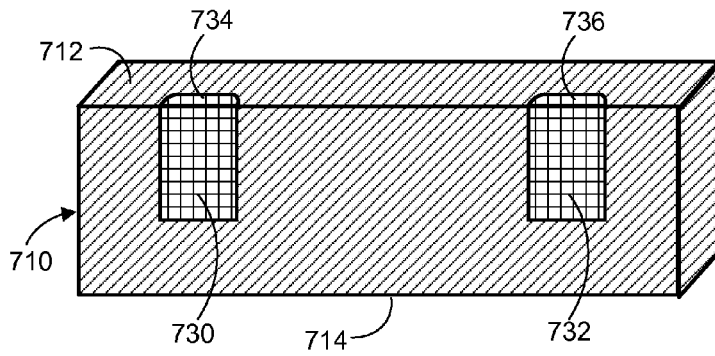


FIG. 7D

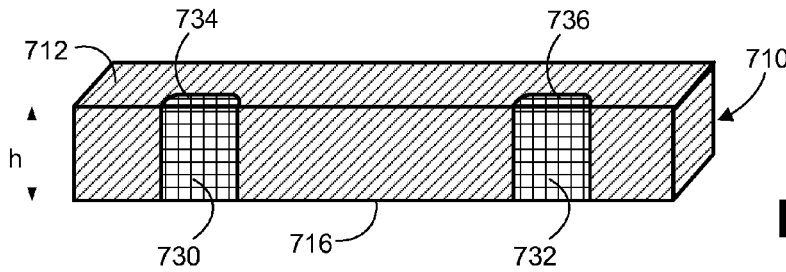


FIG. 7E

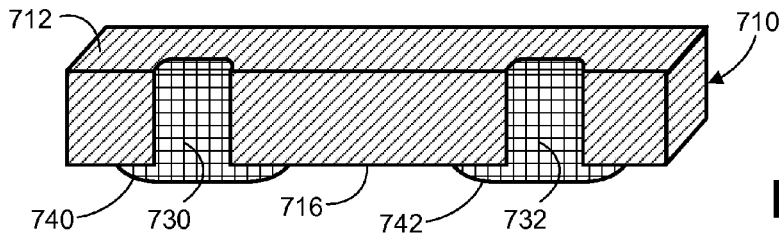


FIG. 7F

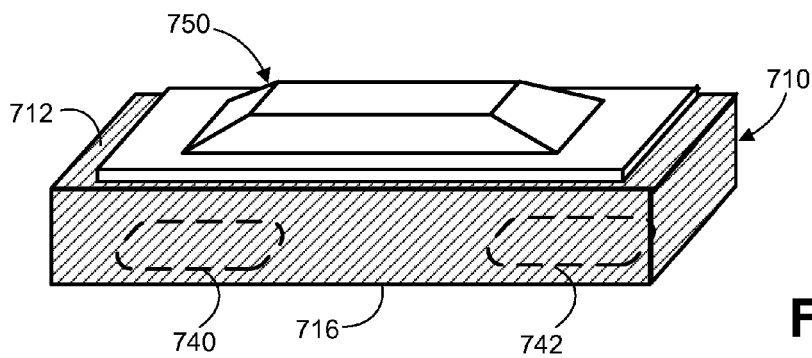
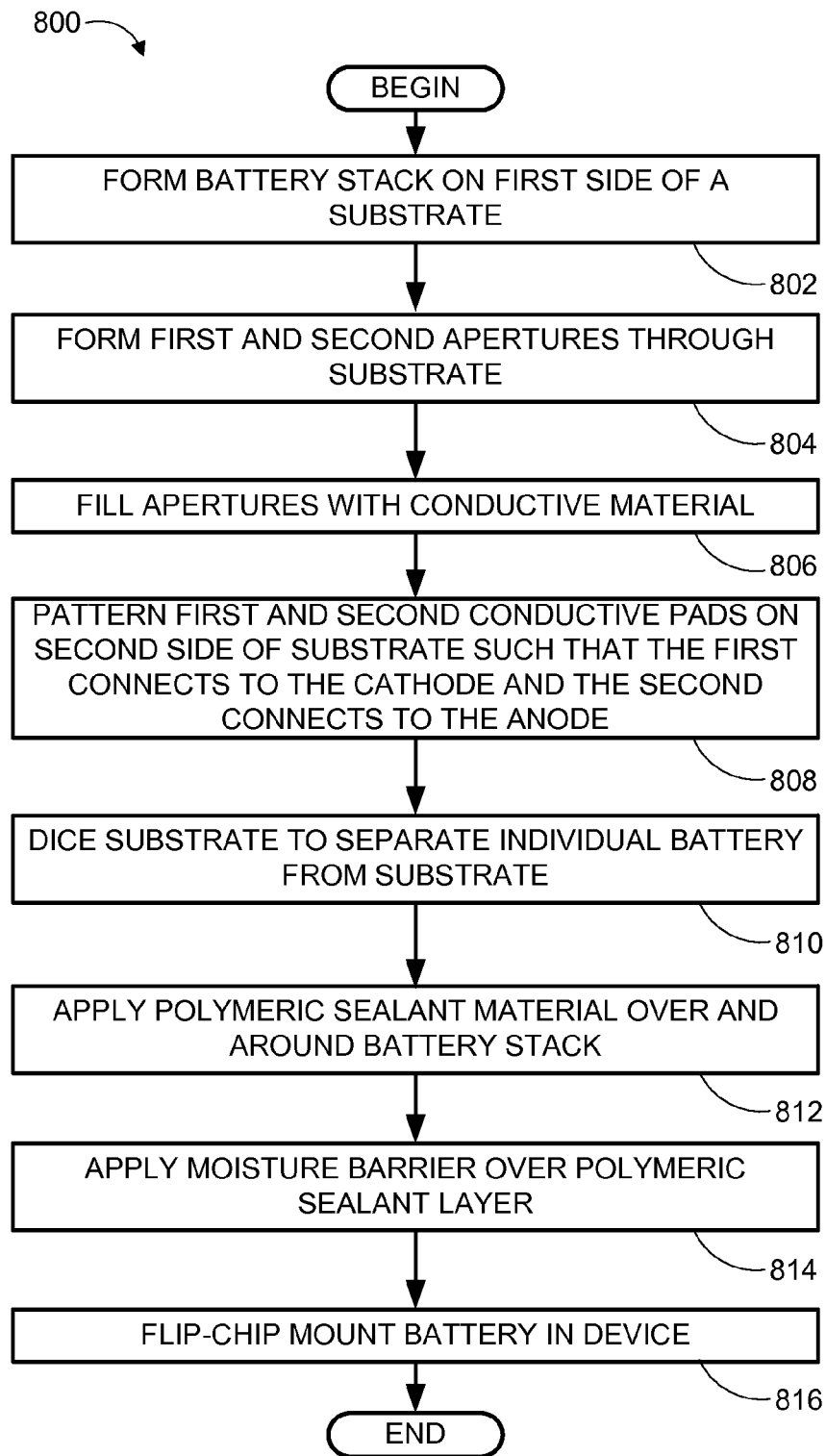


FIG. 7G



**FIG. 8**

## SEALED SOLID STATE BATTERY

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/036,715, filed Aug. 13, 2014, which is incorporated herein by reference in its entirety and for all purposes.

### BACKGROUND

[0002] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0003] Advances in battery technology have enabled the fabrication of tiny, high-energy-density electrochemical batteries capable of powering advanced devices for extended periods of time while occupying small volumes. An electrochemical battery comprises an electrolyte interposed between two electrodes (an anode and a cathode). Electrochemical reactions between the anode and the electrolyte and between the electrolyte and the cathode can cause the development of an electrical potential between the electrodes. Continued electrochemical reactions could drive an electrical current from one electrode, through a device connected to the electrodes, to the opposite electrodes, allowing the device to be powered by the electrical current.

[0004] Lithium ion batteries include a cathode and an anode separated from one another by an electrolyte that transfers lithium ions. During discharge, when the battery is providing current to a circuit connected across the electrodes, redox reactions occur at the two electrodes. Oxidation reactions at the anode ionize lithium, which releases electrons to the connected circuit from the anode, which causes a current to flow through the connected circuit from cathode to anode (i.e., reverse the direction of electron travel). Lithium ions are transferred through the electrolyte from the anode to the cathode to balance the flow of electrons in the circuit. At the cathode, the lithium ions and electrons are reduced. The difference in energy potential between the lithium when at the anode and at the cathode corresponds to the chemically stored energy in the battery. In some cases, lithium batteries may be re-charged by applying a reverse current to the electrodes, which causes lithium ions to traverse the electrolyte in the opposite direction, and to re-supply the anode with lithium.

### SUMMARY

[0005] An electrochemical battery can include electrodes (a cathode and an electrode) arranged on opposite surfaces of an electrolyte. The electrodes and electrolyte can each be solid state films that can be layered on top of one another to create a stacked structure disposed on a substrate. A polymeric sealant material can be applied over and around the battery stack and a moisture barrier can be formed over the sealant material to thereby prevent moisture from reaching the battery. Conductive terminals electrically connected to the cathode and anode, respectively, can then be formed on a second side of the substrate opposite the first side. As such, the battery can be flip-chip mounted to corresponding mounting pads and thereby connected to other electronics that can receive power from the battery.

[0006] Some embodiments of the present disclosure can include a sealed battery. The sealed battery can include a

substrate, a battery stack, a polymeric sealant layer, a first conductive pad, and a second conductive pad. The substrate can have a first side and a second side. The battery stack can be disposed on the first side of the substrate. The battery stack can include a cathode layer, an anode layer, and an electrolyte layer. A first one of the cathode layer and the anode layer can be disposed on the first side of the substrate. The electrolyte layer can be disposed between the cathode layer and the anode layer. The polymeric sealant layer can be formed over and around the battery stack. The first conductive pad can be situated on the second side of the substrate, and can be electrically coupled to the cathode layer. The second conductive pad can be situated on the second side of the substrate, and can be electrically coupled to the anode layer.

[0007] Some embodiments of the present disclosure can include a body-mountable device. The body-mountable device can include a polymeric material formed to have a body-mountable surface, and a sealed battery embedded within the polymeric material. The sealed battery can include a substrate, a battery stack, a polymeric sealant layer, a first conductive pad, and a second conductive pad. The substrate can have a first side and a second side. The battery stack can be disposed on the first side of the substrate. The battery stack can include a cathode layer, an anode layer, and an electrolyte layer. A first one of the cathode layer and the anode layer can be disposed on the first side of the substrate. The electrolyte layer can be situated between the cathode layer and the anode layer. The polymeric sealant layer can be formed over and around the battery stack. The first conductive pad can be situated on the second side of the substrate, and can be electrically coupled to the cathode layer. The second conductive pad can be situated on the second side of the substrate, and can be electrically coupled to the anode layer.

[0008] Some embodiments of the present disclosure can include a method. The method can include forming a battery stack on a first side of a substrate. Forming the battery stack can include: (i) forming a cathode current collector layer on the first side of the substrate such that the cathode current collector layer occupies at least a first region of the first side of the substrate; (ii) forming a cathode active layer on the cathode current collector layer; (iii) forming an electrolyte layer on the cathode active layer; (iv) forming an anode active layer on the electrolyte layer; and (v) forming an anode current collector layer on the anode active layer. A portion of the anode current collector layer can extend beyond the anode active layer and be disposed on the first side of the substrate such that the anode current collector layer occupies at least a second region of the first side of the substrate. The method can also include applying a polymeric sealant layer over and around battery stack to thereby encapsulate the battery stack between the polymeric sealant layer and the substrate. The method can also include applying a moisture barrier over the polymeric sealant layer to thereby inhibit moisture from reaching the polymeric sealant layer and the battery stack. The method can also include forming a first aperture and a second aperture in the substrate. The first aperture can expose, from the second side of the substrate, at least a portion of the cathode current collector. The second aperture can expose, from the second side of the substrate, at least a portion of the anode current collector. The method can also include filling at least a portion of each of the first and second apertures with conductive material to thereby create respective electrical pathways through the substrate. The method can also include forming, on the second side of the substrate, a first conductive

pad that is electrically coupled to the conductive material within the first aperture, such that the first conductive pad is electrically coupled to the cathode current collector layer. The method can also include forming, on the second side of the substrate, a second conductive pad that is electrically coupled to the conductive material within the second aperture, such that the second conductive pad is electrically coupled to the anode current collector layer.

[0009] Some embodiments of the present disclosure include means for forming a battery stack on a first side of a substrate. Some embodiments of the present disclosure include means for applying a polymeric sealant layer over and around battery stack to thereby encapsulate the battery stack between the polymeric sealant layer and the substrate. Some embodiments of the present disclosure include means for applying a moisture barrier over the polymeric sealant layer to thereby inhibit moisture from reaching the polymeric sealant layer and the battery stack. Some embodiments of the present disclosure include means for forming a first aperture and a second aperture in the substrate. Some embodiments of the present disclosure include means for filling at least a portion of each of the first and second apertures with conductive material to thereby create respective electrical pathways through the substrate. Some embodiments of the present disclosure include means for forming, on the second side of the substrate, a first conductive pad that is electrically coupled to the conductive material within the first aperture, such that the first conductive pad is electrically coupled to the cathode current collector layer. Some embodiments of the present disclosure include means for forming, on the second side of the substrate, a second conductive pad that is electrically coupled to the conductive material within the second aperture, such that the second conductive pad is electrically coupled to the anode current collector layer.

[0010] These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a block diagram of an example system that includes a body-mountable device in wireless communication with an external reader.

[0012] FIG. 2A is a bottom view of an example eye-mountable device.

[0013] FIG. 2B is a side view of the example eye-mountable device shown in FIG. 2A.

[0014] FIG. 2C is a side cross-section view of the example eye-mountable device shown in FIGS. 2A and 2B while mounted to a corneal surface of an eye.

[0015] FIG. 2D is a close-in side cross-section view of the example eye-mountable device shown in FIGS. 2A and 2B while mounted to a corneal surface of an eye.

[0016] FIGS. 3A and 3B are side cross-section views of example solid state batteries.

[0017] FIG. 4A is a top aspect view of an example solid state battery with a moisture barrier that terminates along a top surface of a substrate.

[0018] FIG. 4B is a bottom aspect view of the example solid state battery shown in FIG. 4A.

[0019] FIG. 4C is a side cross-section view of the example solid state battery shown in FIG. 4A.

[0020] FIG. 5A is a top aspect view of an example solid state battery with a moisture barrier that terminates along a side surface of a substrate.

[0021] FIG. 5B is a bottom aspect view of the example solid state battery shown in FIG. 5A.

[0022] FIG. 5C is a side cross-section view of the example solid state battery shown in FIG. 5A.

[0023] FIGS. 6A, 6B, 6C, 6D, 6E, 6F, and 6G illustrate stages of fabricating a sealed solid state battery and flip-chip mounting the battery, according to an example embodiment.

[0024] FIGS. 7A, 7B, 7C, 7D, 7E, 7F, and 7G illustrate stages of fabricating a sealed solid state battery and flip-chip mounting the battery, according to an example embodiment.

[0025] FIG. 8 is a flowchart of an example process for fabricating a sealed solid state battery.

#### DETAILED DESCRIPTION

[0026] In the following detailed description, reference is made to the accompanying figures, which form a part hereof. In the figures, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, figures, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

##### I. Overview

[0027] An electrochemical battery can include electrodes (a cathode and an anode) arranged on respective surfaces of an electrolyte. The electrodes and electrolyte can each be solid state films that can be layered on top of one another to create a stacked structure disposed on a substrate. A polymeric sealant material can be applied over and around the battery stack and a moisture barrier can be formed over the sealant material to thereby prevent moisture from reaching the battery. Conductive terminals electrically coupled to the cathode and anode, respectively, can be formed on a second side of the substrate. As such, the battery can be flip-chip mounted to corresponding mounting pads and thereby connected to other electronics that can receive power from the battery.

[0028] The stacked cathode, electrolyte, and anode can be surrounded by a polymeric sealant material that conforms on and around the battery layers to encapsulate the battery between the sealant material and the substrate. A moisture barrier can then be applied over the polymeric sealant material to inhibit moisture from reaching the stacked battery layers and the sealant material. Thus formed, the sealed battery is substantially resistant to deleterious effects of moisture and/or contaminants. The sealed battery may also be integrated into a device that is coated with a biocompatible material, such as a conformal layer of parylene or another material, and used in a biological environment. For instance, the sealed battery may be used in a body-mountable device or implantable device. In some cases, the disclosed battery may be fabricated in bulk by patterning electrode and electrolyte films on a common substrate. The substrate can include con-

ductive vias that electrically couple each electrode to a respective conductive terminal on the opposite side of the substrate.

**[0029]** The substrate with battery cells thereon can then be diced to separate the individual battery cells, and the individual batteries can be sealed by applying sealant material over and around the stacked battery layers. The sealed battery can then be flip-chip mounted to connect to other electronics by bonding the mounting pads to corresponding conductive terminals or traces that provide an electrical connection to the electronics. The mounted battery can then provide power to the connected electronics. In some cases, the sealed battery may be incorporated in a body-mountable device or an implantable device, and used to power electronics in such devices. In such applications, fabrication of the solid state battery can be isolated from fabrication of the other electronics in the device, which allows for such other electronics to be fabricated without restrictions associated with thin film battery fabrication.

**[0030]** For instance, fabricating the battery may involve annealing at relatively high temperatures, such as about 800° C. to crystallize the cathode material, or the battery substrate may be rinsed with harsh solvents at various stages. Therefore, if the battery were assembled directly on the same substrate as other electronics (e.g., chips, sensors, antennas, etc.), the selection of materials and/or processing order would be constrained by the need for compliance with the battery fabrication (e.g., high temperatures, harsh solvents, etc.). Among other factors, such limitations may lead to selecting substrate materials that can withstand 800° C., for example. However, because the battery described herein can be integrated into a device by flip-chip bonding onto corresponding mounting pads, all electronics in the device other than the battery can be fabricated without such limitations. Thus, the substrate on which such other electronics are disposed need not be compliant with temperatures and/or solvents used in the micro-fabrication of the battery itself. For instance, substrates for supporting the remaining electronics may be substrates that are not typically used for battery fabrication, such as polymeric materials (e.g., parylene or polyamide substrates). In addition, the fabrication of the battery can be performed in bulk by simultaneously fabricating a large number of batteries on a common substrate in a single sequence of deposition operations. The common substrate with batteries formed thereon can then be diced to separate the individual batteries. As a result, in addition to providing enhanced design flexibility, the disclosed battery also offers increased efficiency and reduced costs of fabrication.

**[0031]** The fully assembled battery may have a thickness less than 100 micrometers. For example, each of the cathode, electrolyte, and anode layers can have thicknesses of about 2-3 micrometers, so the battery stack can have a total thickness of about 6-10 micrometers. For instance, the cathode may include a deposited layer of lithium cobalt oxide or a similar material; the electrolyte may include a deposited layer of lithium phosphorus oxynitride; and the anode may include a layer of evaporated lithium metal. The substrate with the battery stack disposed on one side and the conductive mounting pads on the other side can have a thickness of about 20-40 micrometers. Such a substrate may be, for example, a silicon chip polished to desired thickness. Finally, the sealant layer and/or moisture barrier can have a thickness of about 10-30 micrometers. The assembled battery can therefore be well suited to use in environments exposed to moisture, such as

mounted to a body of a biological host or implanted within a biological host. In some applications, the total thickness of various layers (and other dimension variables) may be selected in part to provide a target energy storage capacity and/or power delivery, in addition to factors related to size/weight constraints.

**[0032]** In some examples, the disclosed battery may be included in an eye-mountable device similar to a contact lens. The battery can be used to power various bio-interactive electronics in the eye-mountable device. For example, the eye-mountable device may include a sensor for measuring properties of tear fluid. The sealed battery can be flip-chip mounted to conductive pads that connect to additional electronics on a substrate material. That substrate can be embedded within a polymeric material formed to be mounted to an eye surface. The contact lens device can be configured to operate a sensor to obtain a measurement of tear fluid analyte concentration and then use an antenna to communicate the results to an external reader. For instance, a control chip may be connected to the battery, an antenna, and a sensor, all of which may be disposed on a substrate embedded in the polymeric material of the contact lens. The chip can be configured to: (i) receive power from the battery; (ii) operate the sensor to obtain a measurement, and (iii) communicate the measurement using the antenna.

**[0033]** The sensor in such an eye-mountable device (or other body-mountable device) may be an electrochemical sensor for obtaining measurements of an analyte concentration of the tear fluid. The electrochemical sensor can include a working electrode and a reference electrode (or counter electrode) that are exposed to the tear fluid. During measurement, the working electrode can be charged relative to the reference electrode to cause an analyte in the tear fluid to undergo electrochemical reactions at the working electrode. Those reactions result in an amperometric current between the electrodes due to the analyte being electrochemically consumed at the working electrode. The current thus provides an indication of analyte concentration in the tear fluid. The control chip may also operate the antenna to wirelessly communicate sensor measurements, such as an indication of the amperometric current.

**[0034]** In another example, the battery may be used to power electronics in other devices and/or applications. The disclosed sealed solid state battery may be used, for example, in applications with size and/or weight constraints (e.g., devices with thickness less than one millimeter). Examples may include environmental sensors, implantable devices, or other electronics. Small sensors may be coupled to airflows and dispersed to obtain measurements from different locations of particulate concentration, temperature, or other measurements related to air quality. In some instances, sensors or other devices may be integrated into an adhesive substrate, similar to a sticker, which can be affixed to various surfaces. Such adhesive electronic devices may be used, for example, to facilitate air quality measurements or other safety-related measurements experienced by a person wearing the adhesive device on their garments and/or bodies. Adhesive devices may also be affixed to items and used to facilitate identification of parcels, vehicles, or the like by providing active RFID chips powered by the battery integrated in the adhesive device. Many other example applications are possible for sealed solid state batteries.



## II. Example Body-Mountable Electronics Platform

**[0035]** FIG. 1 is a block diagram of a system 100 that includes a body-mountable device 110 in wireless communication with an external reader 180. The body-mountable device 110 is made of a polymeric material 120 formed to be mounted to a body surface. For instance, the polymeric material 120 may be formed to be contact-mounted to a corneal surface of an eye. A substrate 130 is embedded in the polymeric material 120 to provide a mounting location for electronic components such as a power supply 140, a controller 150, bio-interactive electronics 160, and a communication antenna 170. The bio-interactive electronics 160 are operated by the controller 150. The power supply 140 supplies operating voltages to the controller 150 and/or the bio-interactive electronics 160. The antenna 170 is operated by the controller 150 to communicate information to and/or from the body-mountable device 110. The antenna 170, the controller 150, the power supply 140, and the bio-interactive electronics 160 can all be situated on the embedded substrate 130. In applications in which the body-mountable device is arranged to be contact-mounted to an eye, similar to a contact lens, it may also be referred to herein as an ophthalmic electronics platform.

### **[0036]** A. Polymeric Material

**[0037]** The polymeric material 120 can be shaped to include an external surface that is configured to interface with a desired body-mounting location. For example, the polymeric material 120 may include a tooth-mountable surface, a head-mountable surface, an ear-mountable surface, a skin-mountable surface, an eye-mountable surface, and so on. The body-mountable device 110 may also be implemented in a form factor configured to be mounted to other body locations so as to access sample fluids in-vivo, including implantable configurations. For example, the polymeric material 120 may be smooth and include a bio-compatible coating suitable for applications in which the device 110 is implanted under and/or within the skin. The polymeric material 120 may partially or entirely encapsulate electronics within the device 110. In some examples, the body-mountable device 110 may include a mounting surface configured to be mounted to a tooth, a skin surface, a mucous membrane, upon a subcutaneous region, within an interstitial region, or in another region in which in-vivo fluid analyte concentrations may be measured.

**[0038]** To facilitate contact-mounting to an eye, the polymeric material 120 can have a concave surface configured to adhere (“mount”) to a moistened corneal surface (e.g., by capillary forces with tear film coating the corneal surface). Additionally or alternatively, the body-mountable device 110 can be adhered by a vacuum force between the corneal surface and the polymeric material due to the concave curvature. While mounted with the concave surface against the eye, the outward-facing surface of the polymeric material 120 can have a convex curvature that is formed to not interfere with eye-lid motion while the body-mountable device 110 is mounted to the eye. For example, the polymeric material 120 can be a substantially transparent curved polymeric disk shaped similarly to a contact lens.

**[0039]** The polymeric material 120 can include one or more biocompatible materials, such as those employed for use in contact lenses or other ophthalmic applications involving direct contact with the corneal surface. The polymeric material 120 can optionally be formed in part from such biocompatible materials or can include an outer coating with such biocompatible materials. The polymeric material 120 can

include materials configured to moisturize the corneal surface, such as hydrogels and the like. In some embodiments, the polymeric material 120 can be a deformable (“non-rigid”) material to enhance wearer comfort. In some embodiments, the polymeric material 120 can be shaped to provide a predetermined, vision-correcting optical power (e.g., for vision correction applications).

### **[0040]** B. Substrate

**[0041]** The substrate 130 includes one or more surfaces suitable for mounting the bio-interactive electronics 160, the controller 150, the power supply 140, and the antenna 170. The substrate 130 can be used both as a mounting platform for chip-based circuitry (e.g., by flip-chip mounting to conductive terminals patterned on the substrate 130) and/or as a platform for patterning conductive materials (e.g., gold, platinum, palladium, titanium, copper, aluminum, silver, metals, other conductive materials, combinations of these, etc.) to create electrodes, interconnects, connection pads, antenna, etc. In some examples, substantially transparent conductive materials (e.g., indium tin oxide) can be patterned on the substrate 130 to form circuitry, electrodes, etc. For example, the antenna 170 can be fabricated by forming a pattern of gold or another conductive material on the substrate 130 by deposition, photolithography, electroplating, etc. Similarly, interconnects 151, 157 between the controller 150 and the bio-interactive electronics 160, and between the controller 150 and the antenna 170, respectively, can be formed by depositing suitable patterns of conductive materials on the substrate 130. A combination of microfabrication techniques including, without limitation, the use of photoresists, masks, deposition techniques, and/or electroplating techniques can be employed to pattern such materials on the substrate 130.

**[0042]** The substrate 130 can be a relatively rigid material, such as polyethylene terephthalate (“PET”), parylene, and/or another material configured to structurally support the circuitry and/or chip-based electronics within the polymeric material 120. The body-mountable device 110 can alternatively be arranged with a group of unconnected substrates rather than a single substrate. For example, the controller 150 and a sensor included in the bio-interactive electronics 160 can be mounted to one substrate, while the antenna 170 is mounted to another substrate and the two can be electrically connected via the interconnects 157. In another example, the substrate 130 can include separate partitions that each support separated, overlapped coiled portions of the antenna 170. Such as, for instance, an embodiment in which the antenna 170 is divided into multiple windings that wrap around the body-mountable device 110 circumferentially at respective radii, and are connected in parallel and/or in series. To facilitate movement of the individual windings with respect to one another, and thereby enhance flexibility of the body-mountable device 110, and help prevent binding or other deformation of the antenna, the individual windings may each be mounted on separated portions of the substrate 130.

**[0043]** In an eye-mountable application, the substrate 130 (and the bio-interactive electronics 160 thereon) can be positioned away from the area of the device 110 through which light is transmitted to the pupil (e.g., the center of the device). As such, the substrate 130 can avoid interference with light transmission to the central, light-sensitive region of the eye. For example, where the eye-mountable device 110 is shaped as a concave-curved disk, the substrate 130 can be embedded around the periphery (e.g., near the outer circumference) of the disk. In some examples, however, the bio-interactive elec-

tronics **160** (and the substrate **130**) can be positioned in or near the central region of the eye-mountable device **110**. Additionally or alternatively, the bio-interactive electronics **160** and/or substrate **130** can be substantially transparent to incoming visible light to mitigate interference with light transmission to the eye. Moreover, in some embodiments, the bio-interactive electronics **160** can include a pixel array **164** that emits and/or transmits light to be received by the eye according to display instructions. Thus, the bio-interactive electronics **160** can optionally be positioned so as to generate perceivable visual cues to a wearer of an eye-mountable device, such as by displaying information (e.g., characters, symbols, flashing patterns, etc.) on the pixel array **164**.

**[0044]** The dimensions of the substrate **130** can depend on a variety of factors. For instance, in an eye-mountable application, the substrate **130** can be shaped as a flattened ring with a radial width dimension sufficient to provide a mounting platform for the embedded electronics components. The substrate **130** can have a thickness sufficiently small to allow the substrate **130** to be embedded in the polymeric material **120** without influencing the profile of the eye-mountable device. The substrate **130** can have a thickness sufficiently large to provide structural stability suitable for supporting the electronics mounted thereon. For example, the substrate **130** may be shaped as a ring with a diameter of about 10 millimeters, a radial width of about 1 millimeter (e.g., an outer radius 1 millimeter larger than an inner radius), and a thickness of about 50 micrometers. The substrate **130** may be shaped along the surface of an imaginary cone between two circular rings that define an inner radius and an outer radius. In such an example, the surface of the substrate **130** along the surface of the imaginary cone defines an inclined surface that is approximately aligned with the curvature of the eye mounting surface at that radius.

#### **[0045]** C. Power Supply

**[0046]** The power supply **140** is configured to harvest ambient energy to charge a battery **146**, which then supplies DC power **141** to power the controller **150** and bio-interactive electronics **160**. For example, a radio-frequency energy-harvesting antenna **142** can capture energy from incident radio radiation. Additionally or alternatively, solar cell(s) ("photo-voltaic cells") can capture energy from incoming ultraviolet, visible, and/or infrared radiation. Furthermore, an inertial power scavenging system can be included to capture energy from motion of the body-mountable device **110**. The energy harvesting antenna **142** can optionally be a dual-purpose antenna that is also used to communicate information to the external reader **180**. That is, the functions of the communication antenna **170** and the energy harvesting antenna **142** can be accomplished with the same physical component(s).

**[0047]** A rectifier/regulator **144** can be used to condition the captured energy to a stable DC supply voltage **141** that is supplied to the controller **150**. For example, the energy harvesting antenna **142** can receive incident radio frequency radiation. Varying electrical signals on the leads of the antenna **142** are output to the rectifier/regulator **144**. The rectifier/regulator **144** rectifies the varying electrical signals to a DC voltage and regulates the rectified DC voltage to a level suitable for charging the battery **146**. During operation of the device **110**, the battery **146** can supply the DC power **141** to the controller **150** and other embedded electronics **160**, which discharges the battery **146**. Thus, the battery **146** can be a rechargeable electrochemical cell that stores energy in accordance with respective chemical energy states of a cath-

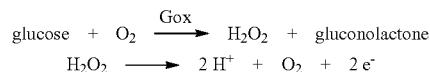
ode and an anode. The battery can include a solid state electrolyte, such as lithium phosphorus oxynitride (LIPON). In such examples, the battery may be formed by layering films of cathode material, electrolyte material, and anode material over one another. Additional examples of solid state batteries that may be integrated into the body-mountable device **110** are described below.

#### **[0048]** D. Controller and Bio-Interactive Electronics

**[0049]** The controller **150** can be turned on when the DC supply voltage **141** is provided to the controller **150**, and the logic in the controller **150** operates the bio-interactive electronics **160** and the antenna **170**. The controller **150** can include logic circuitry configured to operate the bio-interactive electronics **160** so as to interact with a biological environment of the body-mountable device **110**. For instance, one or more components, such as an analyte bio-sensor **162**, can be used to obtain input from the biological environment. Additionally or alternatively, one or more components, such as pixel array **164**, can be used to provide an output to the biological environment.

**[0050]** In one example, the controller **150** includes a sensor interface module **152** that is configured to operate analyte bio-sensor **162**. The analyte bio-sensor **162** can be, for example, an amperometric electrochemical sensor that includes a working electrode and a reference electrode. A voltage can be applied between the working and reference electrodes to cause an analyte to undergo an electrochemical reaction (e.g., a reduction and/or oxidation reaction) at the working electrode. The electrochemical reaction generates an amperometric current that can be measured through the working electrode. The amperometric current is related to the electrochemical reaction rate, which is related to the analyte concentration. Thus, the amperometric current that is measured through the working electrode can provide an indication of analyte concentration. In some embodiments, the sensor interface module **152** can be a potentiostat configured to apply a voltage between working and reference electrodes while measuring a current through the working electrode.

**[0051]** In some instances, a reagent can also be included to sensitize the electrochemical sensor to one or more particular analytes. For example, a layer of glucose oxidase ("GOx") proximal to the working electrode can catalyze glucose oxidation to generate hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). The hydrogen peroxide can then be electrooxidized at the working electrode, which releases electrons to the working electrode, resulting in an amperometric current that can be measured through the working electrode. These reactions are shown below.



**[0052]** The current generated by either reduction or oxidation reactions is approximately proportionate to the electrochemical reaction rate. Further, the reaction rate is dependent on the rate of analyte molecules reaching the electrochemical sensor electrodes to fuel the reactions, either directly or catalytically through a reagent. In a steady state, analyte molecules diffuse to the electrochemical sensor electrodes at approximately the same rate that additional analyte molecules diffuse to the sampled region, and the reaction rate is approximately proportionate to the concentration of the ana-

lyte molecules. The current measured through the working electrode thus provides an indication of the analyte concentration.

**[0053]** The controller **150** can optionally include a display driver module **154** for operating a pixel array **164**. The pixel array **164** can be an array of separately programmable light transmitting, light reflecting, and/or light emitting pixels arranged in rows and columns. The individual pixel circuits can optionally include liquid crystal technologies, microelectromechanical technologies, emissive diode technologies, etc. to selectively transmit, reflect, and/or emit light according to information from the display driver module **154**. Such a pixel array **164** can also optionally include more than one color of pixels (e.g., red, green, and blue pixels) to render visual content in color. The display driver module **154** can include, for example, one or more data lines providing programming information to the separately programmed pixels in the pixel array **164** and one or more addressing lines for setting groups of pixels to receive such programming information. Such a pixel array **164** situated on the eye can also be associated with one or more lenses to direct light to a focal plane perceivable by the eye.

**[0054]** The controller **150** can also include a communication circuit **156** for sending and/or receiving information via the antenna **170**. The communication circuit **156** can optionally include one or more oscillators, mixers, frequency injectors, etc. to modulate and/or demodulate information on a carrier frequency to be transmitted and/or received by the antenna **170**. In some examples, the body-mountable device **110** is configured to indicate an output from a bio-sensor by modulating an impedance of the antenna **170** in a manner that is perceivable by the external reader **180**. For example, the communication circuit **156** can cause variations in the amplitude, phase, and/or frequency of backscatter radiation from the antenna **170**, and such variations can be detected by the reader **180**.

**[0055]** The controller **150** is connected to the bio-interactive electronics **160** via interconnects **151**. For example, where the controller **150** includes logic elements implemented in an integrated circuit to form the sensor interface module **152** and/or display driver module **154**, a patterned conductive material (e.g., gold, platinum, palladium, titanium, copper, aluminum, silver, metals, combinations of these, etc.) can connect a terminal on the chip to the bio-interactive electronics **160**. Similarly, the controller **150** is connected to the antenna **170** via interconnects **157**.

**[0056]** It is noted that the block diagram shown in FIG. 1 is described in connection with functional modules for convenience in description. However, embodiments of the body-mountable device **110** can be arranged with one or more of the functional modules (“sub-systems”) implemented in a single chip, integrated circuit, and/or physical component. For example, while the rectifier/regulator **144** is illustrated in the power supply block **140**, the rectifier/regulator **144** can be implemented in a chip that also includes the logic elements of the controller **150** and/or other features of the embedded electronics in the body-mountable device **110**. Thus, the DC supply voltage **141** that is provided to the controller **150** from the power supply **140** can be a supply voltage that is provided to components on a chip by rectifier and/or regulator components located on the same chip. That is, the functional blocks in FIG. 1 shown as the power supply block **140** and controller block **150** need not be implemented as physically separated modules. Moreover, one or more of the functional modules

described in FIG. 1 can be implemented by separately packaged chips electrically connected to one another.

**[0057]** Additionally or alternatively, the energy harvesting antenna **142** and the communication antenna **170** can be implemented with the same physical antenna. For example, a loop antenna can both harvest incident radiation for power generation and communicate information via backscatter radiation.

**[0058]** E. Reader

**[0059]** The external reader **180** includes an antenna **188** (or a group of multiple antennas) to send and receive wireless signals **171** to and from the body-mountable device **110**. The external reader **180** also includes a computing system with a processor **186** in communication with a memory **182**. The memory **182** can be a non-transitory computer-readable medium that can include, without limitation, magnetic disks, optical disks, organic memory, and/or any other volatile (e.g. RAM) or non-volatile (e.g. ROM) storage system readable by the processor **186**. The memory **182** can include a data storage **183** to store indications of data, such as sensor readings (e.g., from the analyte bio-sensor **162**), program settings (e.g., to adjust behavior of the body-mountable device **110** and/or external reader **180**), etc. The memory **182** can also include program instructions **184** for execution by the processor **186** to cause the external reader **180** to perform processes specified by the instructions **184**. For example, the program instructions **184** can cause external reader **180** to provide a user interface that allows for retrieving information communicated from the body-mountable device **110** (e.g., sensor outputs from the analyte bio-sensor **162**). The external reader **180** can also include one or more hardware components for operating the antenna **188** to send and receive the wireless signals **171** to and from the body-mountable device **110**. For example, oscillators, frequency injectors, encoders, decoders, amplifiers, filters, etc. can drive the antenna **188** according to instructions from the processor **186**.

**[0060]** The external reader **180** can be a smart phone, digital assistant, or other portable computing device with wireless connectivity sufficient to provide the wireless communication link **171**. The external reader **180** can also be implemented as an antenna module that can be plugged in to a portable computing device, such as in an example where the communication link **171** operates at carrier frequencies not commonly employed in portable computing devices. In some instances, the external reader **180** is a special-purpose device configured to be worn relatively near a wearer’s eye to allow the wireless communication link **171** to operate with a low power budget. For example, the external reader **180** can be integrated in a piece of jewelry such as a necklace, earring, etc. or integrated in an article of clothing or an accessory worn near the head, such as a hat, headband, a scarf, a pair of eyeglasses, etc.

**[0061]** In some embodiments, the system **100** can operate to non-continuously (“intermittently”) supply energy to the body-mountable device **110** to power the controller **150** and sensor electronics **160**. For example, radio frequency radiation **171** can be supplied to power the body-mountable device **110** long enough to operate the sensor electronics **160** and communicate an outcome of such operation. In such an example, the supplied radio frequency radiation **171** can be considered an interrogation signal from the external reader **180** to the body-mountable device **110** to request feedback (e.g., a sensor measurement). By periodically interrogating the body-mountable device **110** (e.g., by supplying radio

frequency radiation **171** to temporarily turn the device on), the external reader **180** can accumulate a set of measurements (or other feedback) over time from the sensor electronics **160** without continuously powering the body-mountable device **110**.

#### [0062] F. Example Operation

[0063] In practice, the power supply **140** can function to harvest energy from received radio frequency radiation using the energy harvesting antenna **142** and the rectifier/regulator **144**, and the harvested energy can be used to charge the battery **146**. For example, radio frequency radiation can cause radio frequency electrical signals on leads of the antenna **142**. The rectifier **146** can be connected to the antenna leads and convert the radio frequency electrical signals to a DC voltage, which can be applied to the battery **146** to create a charging current. The battery **146** can then output supply voltages (i.e., the DC power **141**) to operate the hardware logic of the controller **150** and also to power the electrochemical sensor **162**. The DC supply voltage(s) **141** may be voltages suitable for driving digital logic circuitry, such as approximately 1.2 volts, approximately 3 volts, etc. In some examples, reception of the radio frequency radiation from the external reader **180** (or another source, such as ambient radiation, etc.) causes the supply voltages **141** to be supplied to the sensor **162** and hardware logic of the controller **150**, thereby activating the body-mountable device **110**. While powered, the sensor **162** and sensor interface **152** of the controller **150** are configured to generate and measure a current indicative of analyte concentration and communicate the results.

[0064] The external reader **180** associates the backscatter signal **171** with the sensor result (e.g., according to a pre-programmed relationship associating impedance of the antenna **170** with output from the sensor **162** using look-up tables, calibration information, etc.). The reader **180** can then store the indicated sensor results (e.g., analyte concentration values) in a local memory and/or an external data storage (e.g., by communicating through a network).

[0065] In some embodiments, one or more of the features shown as separate functional blocks can be implemented (“packaged”) on a single chip. For example, the body-mountable device **110** can be implemented with a rectifier **144**, voltage regulator, sensor interface **152**, and other hardware logic packaged together in a single chip or controller module. In some cases, the battery **146** may be electrically coupled to such a chip via conductive traces that terminate with mounting pads on which the battery **146** can be flip-chip mounted. The controller chip can also have interconnects (“leads”) connected to the loop antenna **170** and the analyte bio-sensor **162** is disposed, which may be disposed on a sensor chip that is flip-chip mounted over conductive mounting pads, for example. Such a controller operates to harvest energy received at the loop antenna **170**, apply a voltage between the electrodes of the sensor **162** sufficient to develop an amperometric current, measure the amperometric current, and indicate the measured current via the antenna **170** (e.g., through the backscatter radiation **171**).

#### [0066] G. Example Eye-Mountable Electronics Platform

[0067] FIG. 2A is a top view of an example eye-mountable device **210** (or ophthalmic electronics platform). FIG. 2B is an aspect view of the example eye-mountable device shown in FIG. 2A. It is noted that relative dimensions in FIGS. 2A and 2B are not necessarily to scale, but have been rendered for purposes of explanation only in describing the arrangement of the example device **210**. The eye-mountable device **210**

can be formed of a polymeric material **220** shaped as a curved disk. The eye-mountable device **210** includes a loop antenna **270**, a controller **250**, and an electrochemical battery **260** mounted on a substrate **230** that is embedded in the polymeric material **220**. The eye-mountable device **210** may also include an electrochemical sensor used to obtain a measurement of analyte concentration in tear film surrounding the device **210**.

[0068] The polymeric material **220** can be a substantially transparent material to allow incident light to be transmitted to the eye while the eye-mountable device **210** is mounted to the eye. The polymeric material **220** can be a biocompatible material similar to those employed to form vision correction and/or cosmetic contact lenses in optometry, such as polyethylene terephthalate (“PET”), polymethyl methacrylate (“PMMA”), polyhydroxyethylmethacrylate (“polyHEMA”), silicone hydrogels, combinations of these, etc. The polymeric material **220** can be formed with one side having a concave surface **226** suitable to fit over a corneal surface of an eye. The opposite side of the disk can have a convex surface **224** that does not interfere with eyelid motion while the eye-mountable device **210** is mounted to the eye. A circular outer side edge **228** connects the concave surface **226** and convex surface **224**. The polymeric material **220** can be formed with a curved shape in a variety of ways. For example, techniques similar to those employed to form vision-correction contact lenses can be employed to form the polymeric material **220**, such as heat molding, injection molding, spin casting, etc.

[0069] The eye-mountable device **210** can have dimensions similar to a vision correction and/or cosmetic contact lenses, such as a diameter of approximately 1 centimeter, and a thickness of about 0.1 to about 0.5 millimeters. However, these diameter and thickness values are provided for example purposes only. In some embodiments, the dimensions of the eye-mountable device **210** can be selected according to the size and/or shape of the corneal surface of the wearer’s eye, to accommodate one or more components embedded in the polymeric material **220**, and/or to achieve a target optical correction.

[0070] While the eye-mountable device **210** is mounted in an eye, the convex surface **224** faces outward to the ambient environment while the concave surface **226** faces inward, toward the corneal surface. The convex surface **224** can therefore be considered an outer, top surface of the eye-mountable device **210** whereas the concave surface **226** can be considered an inner, bottom surface. The “top” view shown in FIG. 2A is an illustration facing the convex surface **224**.

[0071] The substrate **230** can be embedded in the polymeric material **220** so as to be situated along the outer periphery **222** of the polymeric material **220**, away from the central region **221**. The substrate **230** can be shaped as a flat, circular ring (e.g., a disk with a central hole). The flat surface of the substrate **230** (e.g., along the radial width) serves as a platform for mounting electronics such as chips (e.g., via flip-chip mounting) and for patterning conductive materials (e.g., via microfabrication techniques such as photolithography, deposition, plating, etc.) to form electrodes, antenna(e), mounting pads, and/or interconnections. Both the substrate **230** and the polymeric material **220** can be approximately cylindrically symmetric about a common central axis. The substrate **230** can have, for example, a diameter of about 10 millimeters, a radial width of about 1 millimeter (e.g., an outer radius 1 millimeter greater than an inner radius), and a thickness of about 50 micrometers. However, these dimen-

sions are provided for example purposes only, and in no way limit the present disclosure. The substrate **230** can be implemented to assume a variety of different form factors, similar to the discussion of the substrate **130** in connection with FIG. 1 above.

[0072] The controller **250** can be a chip including logic elements configured to operate an electrochemical sensor and the loop antenna **270**. The controller chip **250** (and any other electronics on the substrate **230**) can receive power from the battery **260**. The controller **250** is electrically connected to the loop antenna **270** by interconnects **257** also situated on the substrate **230**. Similarly, the controller **250** is electrically connected to the battery **260** by interconnects **251**. The interconnects **251**, **257**, the loop antenna **270**, and conductive electrodes included in the sensor **260** can be formed from conductive materials patterned on the substrate **230** by a process for precisely patterning such materials, such as deposition, photolithography, etc. The interconnects **251** that electrically couple the battery **260** to the chip **250** may include traces that terminate with a pair of conductive mounting pads. The battery **260** may then be flip-chip bonded over the mounting pads to thereby electrically couple the battery **260** to the electronics in the device **210**. The conductive materials patterned on the substrate **230** can be, for example, gold, platinum, palladium, titanium, carbon, aluminum, copper, silver, silver-chloride, conductors formed from noble materials, metals, combinations of these, etc.

[0073] The loop antenna **270** is a layer of conductive material patterned along the flat surface of the substrate to form a flat conductive ring. In some examples, to allow additional flexibility along the curvature of the polymeric material, the loop antenna **270** can include multiple substantially concentric sections electrically joined together in parallel or in series. Each section can then flex independently along the concave/convex curvature of the eye-mountable device **210**. In some examples, the loop antenna **270** can be formed without making a complete loop. For instances, the antenna **270** can have a cutout to allow room for the controller **250** and the sensor **260**, as illustrated in FIG. 2A. However, the loop antenna **270** can also be arranged as a continuous strip of conductive material that wraps entirely around the flat surface of the substrate **230** one or more times, and such strips can be connected in parallel and/or series to achieve desired signal performance. For example, a strip of conductive material with multiple windings can be patterned on the side of the substrate **230** opposite the controller **250** and sensor **260**. Interconnects between the ends of such a wound antenna (e.g., the antenna leads) can then be passed through the substrate **230** to the controller **250**.

[0074] FIG. 2C is a side cross-section view of the example eye-mountable electronic device **210** while mounted to a corneal surface **22** of an eye **10**. FIG. 2D is a close-in side cross-section view enhanced to show the tear film layers **40**, **42** surrounding the surfaces **224**, **226** of the example eye-mountable device **210**. It is noted that relative dimensions in FIGS. 2C and 2D are not necessarily to scale, but have been rendered for purposes of explanation only in describing the arrangement of the example eye-mountable electronic device **210**. For example, the total thickness of the eye-mountable device can be about 100-200 micrometers, while the thickness of the tear film layers **40**, **42** can each be about 10 micrometers, although this ratio may not be reflected in the drawings. Some aspects are exaggerated to allow for illustration and to facilitate explanation.

[0075] The eye **10** includes a cornea **20** that is covered by bringing the upper eyelid **30** and lower eyelid **32** together over the top of the eye **10**. Incident light is received by the eye **10** through the cornea **20**, where light is optically directed to light-sensing elements of the eye **10** (e.g., rods and cones, etc.) to stimulate visual perception. The motion of the eyelids **30**, **32** distributes a tear film across the exposed corneal surface **22** of the eye **10**. The tear film is an aqueous solution secreted by the lacrimal gland to protect and lubricate the eye **10**. When the eye-mountable device **210** is mounted in the eye **10**, the tear film coats both the concave and convex surfaces **224**, **226** with an inner layer **40** (along the concave surface **226**) and an outer layer **42** (along the convex layer **224**). The tear film layers **40**, **42** can be about 5 to 10 micrometers in thickness and together account for about 5 to 10 microliters.

[0076] The tear film layers **40**, **42** are distributed across the corneal surface **22** and/or the convex surface **224** by motion of the eyelids **30**, **32**. For example, the eyelids **30**, **32** may raise and lower, respectively, to spread a small volume of tear film across the corneal surface **22** and/or the convex surface **224** of the eye-mountable device **210**. The tear film layer **40** on the corneal surface **22** also facilitates mounting the eye-mountable device **210** by capillary forces between the concave surface **226** and the corneal surface **22**.

[0077] As shown in the cross-sectional views in FIGS. 2C and 2D, the substrate **230** can be inclined such that the flat mounting surfaces of the substrate **230** are approximately parallel to an adjacent portion of the convex surface **224**. The substrate **230** can be a flattened ring with an inward-facing surface **232** (closer to the concave surface **226** of the polymeric material **220**) and an outward-facing surface **234** (closer to the convex surface **224**). The substrate **230** can have electronic components and/or patterned conductive materials mounted to either or both mounting surfaces **232**, **234**. As shown in FIG. 2D, the electrochemical battery **260**, controller **250**, and conductive interconnect **251** are mounted on the outward-facing surface **234**. In particular, the battery **260** is mounted on a pair of conductive mounting pads disposed on the outward-facing surface **234**. The mounting pads are aligned with corresponding terminals on the battery **260**, one of which is electrically coupled to an anode of the battery **260**, the other of which is electrically coupled to a cathode of the battery **260**. Other electronics, electrodes, etc. situated on the substrate **230** may be mounted to either the inward-facing side **232** or the outward-facing side **234**. Moreover, in some embodiments, some electronic components can be mounted on one side (e.g., **232**), while other electronic components are mounted to the opposing side (e.g., **234**), and connections between the two sides can be made through conductive materials passing through the substrate **230**. For example, an electrochemical analyte sensor may be disposed on the substrate **230** and electrically coupled to the controller **250** via interconnects patterned on the substrate **230**. The controller **250** can use the electrochemical sensor to obtain measurements of tear film analyte concentration by applying a voltage to the electrodes of the electrochemical sensor and monitoring the resulting amperometric current through the working electrode. The controller **250** can then use the antenna **270** to indicate the measured current.

[0078] The battery **260** includes two electrodes: an anode and a cathode. The anode and the cathode can be separated by an electrolyte which transfers ions during charge or discharge of the battery **260**. The transfer of ions through the electrolyte is balanced by electrons conveyed between the electrodes

through the connected circuit. The resulting current flow through the external circuit during battery discharge. During a charge operation, the battery drains current from the external circuit. The battery 260 may be implemented on a battery substrate separate from the substrate 230. For instance, the battery 260 can have electrodes interposed by an electrolyte patterned on one side of the battery substrate, and each electrode can be connected to a conductive pad on the reverse side of the battery substrate. The battery 260 can then be mounted over corresponding conductive pads formed on the substrate 230. In other examples, a battery may be formed directly on the substrate 230 and interconnected with other electronics on the same substrate.

### III. Example Thin Film Batteries

[0079] FIG. 3A illustrates an example arrangement for a thin film battery 300. FIG. 3B illustrates another example arrangement for a thin film battery 340. To illustrate internal structures, FIGS. 3A and 3B show cross-sectional views of the batteries 300, 340. The arrangements illustrated by FIGS. 3A and 3B are not drawn to scale and are rendered so as to facilitate understanding. For example, some aspects may be exaggerated to facilitate illustration. The batteries 300, 340 can be included in an eye-mountable device for detecting a tear film concentration of an analyte (e.g., the eye-mountable device 210 described in connection with FIGS. 2A-2D above), in a body-mountable or implantable device, or in another electronic device with a relatively thin form factor and/or size/weight constraints.

[0080] Referring to FIGS. 3A and 3B, the batteries 300, 340 may be solid state batteries that are formed by films of electrode material separated by an electrolyte film. The layered films may be formed by deposition, evaporation, and/or other microfabrication techniques, and the composition of each film can be selected to provide particular battery chemistries. For instance, in a lithium ion solid state battery, the electrolyte layer may be formed of lithium phosphorus oxynitride (LIPON) (e.g., formed by sputtering with a lithium orthophosphate target); the cathode may be formed of lithium cobalt oxide ( $\text{LiCoO}_2$ ) and the anode may be formed of lithium metal. Other examples of electrode and electrolyte film materials are also possible. In addition, the two electrode films can have a conductive layer opposite the electrolyte film to conduct current between the electrodes and an external circuit. Such thin film batteries may be formed by layering materials over a substrate beginning with the cathode (as in FIG. 3A) or beginning with the anode (as in FIG. 3B). The batteries 300, 340 are described below with reference to example processes of formation, although the assembled arrangements may be formed by other fabrication techniques and the disclosed battery arrangements are not limited to any one particular fabrication technique. In addition, the dimensional extent and/or thickness of each layer of the battery may be selected, at least in part, to achieve a desired energy storage capacity and/or power delivery capacity. In some cases, batteries disclosed herein may be designed to provide between about 1  $\mu\text{Ah}$  and about 5  $\mu\text{Ah}$ , although other values are also possible. Moreover, in some applications, one or more battery cells may be connected to one another in series or in parallel to achieve a desired energy storage capacity and/or power delivery capacity. Thus, example layer thicknesses noted below are provided for example purposes only.

[0081] Referring to FIG. 3A, the battery 300 is disposed on a substrate 320 which has a first side 322 and a second side

324. The substrate 320 can be a silicon-based material such as a silicon wafer or a mica substrate, a ceramic or metal substrate, or a polymeric substrate such as polyethylene terephthalate (PET), polyimide, parylene, or another plastic substrate. Depending on fabrication constraints, the substrate 320 may be selected based on tolerance to various annealing temperatures, such as temperatures up to 800° C. The substrate 320 can have a thickness sufficient to provide structural stability to the battery during handling and fabrication, but may be less than 100 micrometers in thickness. For instance, the substrate may be a silicon wafer polished to a thickness between about 20 micrometers and about 50 micrometers. In some applications, the thickness of the substrate 320 is selected such that the total thickness of the fabricated battery is less than 100 micrometers, for example.

[0082] A cathode current collector layer 302 can be disposed on the first side 322 of the substrate 320. In some examples, the first side 322 of the substrate 320 may be prepared by polishing and/or cleaning the first side 322 to provide a surface that is free of contaminants and in a desired form factor (e.g., substantially planar). The first side 322 may optionally be coated with a passivation layer such as an insulating film. A passivation layer may be used to prevent potential conduction through the substrate 320, such as may occur in conductive or semi-conductive substrate material. The cathode current collector layer 302 can be sputter deposited in a desired pattern (e.g., using photoresists, masks, etc.) to occupy a first area of the first side 322. The cathode current collector layer can be formed of a conductive material such as titanium, cobalt, gold, molybdenum, platinum, palladium, another metal, combinations of these, etc. The cathode current collector layer 302 may have a thickness between about 300 angstroms and about 500 angstroms (i.e., 30-50 nanometers).

[0083] A film of cathode material 304 can be disposed over the cathode current collector layer 302. The cathode material 304 can be patterned (e.g., in a deposition process) so as to be substantially only over the cathode current collector layer 302 (e.g., using resists, masks, etc.). For instance, if the cathode current collector layer 302 occupies a particular region of the first side 322, the cathode material 304 may be entirely disposed within that same region. The cathode material 304 can be a material which reduces lithium ions transferred from the anode. For example, the cathode material 304 can include lithium cobalt oxide ( $\text{LiCoO}_2$ ), or another lithium salt, metal salt, or cobalt oxide salt. The cathode material 304 may have a thickness between about 1 micrometer and about 10 micrometers. The energy density of the cathode material can be increased after deposition by annealing the cathode material 304 (and substrate), which causes the material to crystallize in an arrangement favorable for receiving lithium. For example, a  $\text{LiCoO}_2$  film may be annealed at a temperature between about 500° C. and about 800° C. Other techniques may be used to achieve crystallization. For instance, in examples in which the substrate material 320 cannot withstand a high annealing temperature, the cathode material 304 may be crystallized using laser annealing or by exposing the cathode material to argon and oxygen plasma; bombardment with reactive oxygen ions can then crystallize the cathode material 304 without heating the substrate 320.

[0084] A film of electrolyte material 306 can be disposed over the cathode material 304. The film of electrolyte material may be sputter deposited over the cathode material 304. The electrolyte material 306 can be a layer of material such as

lithium phosphorous oxynitride (LIPON). The electrolyte material **306** can have a thickness between about 1.5 micrometers and about 3 micrometers. The electrolyte may also be annealed to achieve a target energy state of the electrolyte (e.g., LIPON may be annealed at about 250° C.). To form the electrolyte film, LIPON can be sputter deposited using a target of lithium orthophosphate, and can be patterned in a region that overlaps the cathode material **304**. As shown in FIG. 3A, the electrolyte material **306** may fully encapsulate the cathode material **304** between the cathode current collector layer **302** and the electrolyte material **306**. For instance, the electrolyte material **306** can be patterned in a region that includes the entirety of the cathode material **304** and also extends beyond the side edges of the cathode material **304**. As such, the cathode layer **304** can only receive electrical connections through the electrolyte layer **306** or through the cathode current collector layer **302**.

[0085] A film of anode material **308** can be disposed over the electrolyte material **306**. The anode material **308** may be evaporated lithium metal and can have a thickness of about 2 to about 3 micrometers. The anode material **308** can be patterned over a region that is entirely within the area occupied by the electrolyte material **306**. Because the electrolyte material **306** overlaps the electrolyte material **304**, the cathode layer **304** is separated from the anode material **308** at all locations by the electrolyte material **306**, and no direct contact is made between the anode and cathode materials **304**, **308**.

[0086] An anode current collector layer **310** can be disposed over the anode layer **308**. The anode current collector layer can be a layer of conductive material (similar to the cathode current collector layer), but the anode current collector layer **310** can extend beyond the region occupied by the anode **308**, electrolyte **306**, cathode **304**, and cathode current collector **302**. Thus, the anode current collector layer **310** can be patterned as a continuous strip of conductive material that is disposed over the anode material **308** and also makes contact with a region of the first side **322** of the substrate **320** that is not occupied by the cathode current collector layer **302**. Preferably, the areas on the first side **322** of the substrate **320** occupied by the cathode current collector layer **302** and the anode current collector layer **310** can be separated from one another by an insulator (e.g., to prevent direction conduction between the cathode and anode current collectors). In FIG. 3A, the two current collector layers **302**, **310** are separated by a portion of the electrolyte layer **306** that contacts the first side **322** of the substrate **320**.

[0087] The assembled battery stack of layered electrodes and electrolyte material can be coupled to an external circuit via connection with the two current collector layers **302**, **310** at respective terminals **312**, **314**. The terminals **312**, **314** may be integrally formed portions of the current collector layer that are conveniently accessible for forming interconnections with the battery. For instance, conductive traces or other interconnects may be connected on the first side **322** at the cathode terminal **312** and the anode terminal **314**. Additionally or alternatively, as shown in FIG. 3A, vias **330**, **334** can be formed through the substrate **320** aligned with each of the connection terminals **312**, **314**. The vias **330**, **334** can be apertures through the substrate formed by laser ablation, deep reactive ion etching, or another process, that are at least partially filled with conductive material. The conductive material

within the vias **330**, **334** thereby provide electrical paths between each of the terminals **312**, **314** and the second side **324** of the substrate **320**.

[0088] Conductive mounting pads **332**, **336** can be formed on the second side **324** of the substrate **324** over each of the vias **330**, **334**. For example, a first mounting pad **332** (on the second side **324**) can be electrically coupled to the cathode current collector layer **302** (on the first side **322**) through the first via **330**, and a second mounting pad **336** (on the second side **324**) can be electrically coupled to the anode current collector layer **310** (on the first side **322**) through the second via **334**. The mounting pads **332**, **336** can be patterned on the second side **324** in any non-overlapping manner. For instance, each of the mounting pads **332**, **336** may occupy substantially half of the second side **324** of the substrate **320**. The assembled battery **300** can then be electrically coupled to another circuit by flip-chip mounting the mounting pads **332**, **336** over corresponding terminals.

[0089] Referring to FIG. 3B, the battery **340** is disposed on a substrate **360** which has a first side **362** and a second side **364**. An anode current collector layer **342** is disposed on the first side **362** of the substrate **360**. A film of anode material **344** is disposed over the anode current collector layer **342**. A film of electrolyte material **346** is disposed over the anode material **344**. A film of cathode material **348** is disposed over the electrolyte material **346**. And a cathode current collector layer **350** is disposed over the cathode material **348**. The current collector layers, electrode films, and electrolyte film in FIG. 3B can be the same or similar to the current collector layers, electrode films, and electrolyte film described in connection with FIG. 3A. However, because the anode material **344** and electrolyte material **346** are disposed on the substrate **360** prior to the cathode material **348**, the cathode material **348** may not undergo a high temperature annealing process. For example, the cathode material **348** may be crystallized by a process involving oxygen bombardment in argon oxygen plasma and/or laser annealing.

[0090] The assembled battery stack includes an anode terminal **352** and a cathode terminal **354** disposed on the first side **362** of the substrate **360**. Vias **370**, **374** through the substrate **360** electrically couple the anode terminal **352** and the cathode terminal **354** to respective conductive mounting pads **372**, **376** formed on the second side **364** of the substrate **360**.

[0091] The example arrangements described in connection with FIGS. 3A and 3B illustrate single battery cells (e.g., a single electrolyte in contact with a cathode, and an anode in contact with the electrolyte but not the cathode). In some examples, multiple solid state battery cells arranged in accordance with the battery **300** or the battery **340** may be formed on a common substrate (e.g., by patterning respective layers of current collector layers, electrode films, and electrolyte film). Vias and conductive mounting pads can be formed on an opposite side of the common substrate before or after formation of the battery cells. The individual battery cells can then be separated from one another by dicing the substrate or laser scribing the substrate. The individual batteries can then be integrated into electronics devices by flip-chip mounting the batteries onto corresponding conductive pads.

[0092] Forming multiple batteries on a common substrate offers several advantages during device fabrication. First, fabrication of the batteries is more efficient when multiple batteries are formed simultaneously using a common substrate that is then diced, because a single series of vacuum

deposition operations can be used to fabricate multiple batteries. Second, because the batteries are fabricated separately from the electronics that they will be powering, the fabrication of those other electronics is not subject to constraints involved in the battery formation. For instance, battery fabrication may involve the use of high temperatures, harsh solvents, etc. In applications in which batteries are formed directly on a substrate with other electronics, those other electronics and substrate are subjected to the same conditions involved in battery fabrication, which may constrain selection of materials, order of processing steps, or other factors. Separating battery fabrication from the fabrication of other electronics, and then flip-chip mounting the individual batteries via pick and place operations is therefore more efficient and offers greater flexibility in selection of materials and operations.

#### IV. Example Sealed Thin Film Batteries

[0093] FIGS. 4A, 4B, and 4C illustrate an example sealed battery 400. FIGS. 5A, 5B, and 5C illustrate another example sealed battery 500. The example sealed batteries described in FIGS. 4A-5C each include a battery cell disposed on a substrate. The battery cell includes an electrolyte film in contact with a cathode film, and an anode film in contact with the electrolyte film but not in contact with the cathode film. The battery stack may take the form of either of the example thin film batteries 300, 340 described in connection with FIGS. 3A and 3B. Each of the sealed batteries also include a pair of conductive mounting pads situated on the opposite side of the substrate from the side the battery is disposed on, with one being electrically coupled to the cathode and the other electrically coupled to the anode. In addition, the example sealed batteries include polymeric sealant material that encapsulates the battery stack between the sealant material and the substrate, and a moisture barrier that is disposed on the sealant material.

[0094] FIG. 4A is a top aspect view of an example solid state battery 400 with a moisture barrier 420 that terminates along a top surface 412 of a substrate 410. FIG. 4B is a bottom aspect view of the example solid state battery 400. FIG. 4C is a side cross-section view of the example solid state battery 400. The battery 400 includes a substrate 410, a battery stack 402 disposed on the substrate 410, a polymeric sealant material 404 disposed over and around the battery stack 402, and a moisture barrier 420 disposed on the polymeric sealant material 404. The battery stack 402 is formed on a first side 412 of the substrate 410, whereas conductive mounting pads 430, 432 that are electrically coupled to the anode and cathode of the battery stack 402, respectively, are formed on the second side 414 of the substrate 410.

[0095] The polymeric sealant material 404 can be a low temperature polymeric formulation, such as a polymer that becomes deformable above a particular temperature (e.g., between about 100° C. and about 200° C.). For instance, the polymeric sealant material 404 may be a polyethylene material, a polyamide material, polypropylene material, or any other thermoplastic or thermosetting polymer. The polymeric sealant material 404 may be applied over and around the battery stack 402 by an applicator that spreads the sealant material 404 over and around the battery stack 402. The polymeric sealant material 404 can then conform over and around the sides of the battery stack 402 (e.g., by flowing) and create a continuous seal along the first side 412 of the substrate 410 that entirely surrounds the battery stack 402, which

is disposed on the substrate 410. The polymeric sealant material 404 may also be applied by spin coating or spraying the sealant material 404 to form a continuous layer above and around the battery stack 402. Because the polymeric sealant material 404 can form a continuous layer that seals against the substrate 410 on all sides of the battery stack 402, the polymeric sealant material can encapsulate the battery stack 402 between the sealant material 404 and the first side 412 of the substrate 410. The polymeric sealant material 410 also provides a support for the moisture barrier 420 that is disposed thereon. Thus, the polymeric sealant material 404 creates a separation between the battery stack 402 and the moisture barrier 420. In some cases, moreover, the moisture barrier may be omitted, and the polymeric sealant material 404 may inhibit moisture from reaching the battery stack 402. In such examples, the polymeric sealant material 404 may be a biocompatible material such as parylene or another biocompatible material, and/or may be substantially resistant to water swelling.

[0096] The moisture barrier 420 is disposed on the polymeric sealant material 404 to inhibit moisture from reaching the polymeric sealant material 404 and the battery stack 402. In some examples, the moisture barrier 420 can be a metallic or ceramic layer that is deposited over the polymeric sealant material 404 by a sputtering process. In some examples, the moisture barrier 420 may be a flexible foil that is applied over the polymeric sealant material 404. As shown in FIG. 4C, the moisture barrier 420 can have a raised top region 422 that is approximately parallel to the substrate 410, a transition region 426 that trends toward the substrate 410 from the raised top region 422, and side edges 424 where the moisture barrier 420 is closest to the substrate 410. The moisture barrier terminates along the first side 412 of the substrate 410 at an outer edge 428. The raised top region 422 can approximately correspond to the region spanned by the battery stack 402 on the substrate 410. The moisture barrier 420 is a continuous film or foil that is substantially impervious to moisture, and so the only moisture that can reach the polymeric sealant material 404 must enter along the first side 412 of the substrate 410, immediately below the outer edge 428.

[0097] Some implementations of the battery 400 may be fabricated so as to reduce the distance between the outer edge 428 and the first side 412 of the substrate 410 within fabrication limitations. Some techniques may involve compressing the side edges 424 against the substrate 410. Some techniques may involve, prior to sputtering the moisture barrier 420, removing some of the polymeric sealant material 404 from the substrate 410 so as to expose a continuous ring on the first side 412 of the substrate 410 that entirely surrounds the battery stack 402. The sputtered moisture barrier may then adhere directly against the first side 412 of the substrate 410 in the continuous ring.

[0098] In some examples, the moisture barrier 420 can be compressed against the substrate 410 by applying pressure around the side edges 424 thereof. The shape can be held, at least in part, by cooling the thermoplastic polymeric sealant material 404, which causes the polymeric sealant material 404 to harden, and thereby fix the shape of the moisture barrier 420. In some examples, the polymeric sealant material 404 may be formed to take a shape suitable for receiving a sputtered moisture barrier material (e.g., by applying a mold to the sealant material 404), and then the moisture barrier 420 can be sputtered onto the formed sealant material 404. Alternative techniques for applying the moisture barrier are also



possible. Moreover, in some cases, the moisture barrier can be applied solely to the top surface of the moisture barrier in a layer that is substantially parallel to the plane of the substrate on which the battery stack is disposed.

[0099] FIG. 5A is a top aspect view of an example solid state battery 500 with a moisture barrier 520 that terminates along a side surface 516 of a substrate 510. FIG. 5B is a bottom aspect view of the example solid state battery 500. FIG. 5C is a side cross-section view of the example solid state battery 500. The battery 500 includes a substrate 510, a battery stack 502 disposed on the substrate 510, a polymeric sealant material 504 disposed over and around the battery stack 502, and a moisture barrier 520 disposed on the polymeric sealant material 504. The battery stack 502 is formed on a first side 512 of the substrate 510, whereas conductive mounting pads 530, 532 that are electrically coupled to the anode and cathode of the battery stack 502, respectively, are formed on the second side 514 of the substrate 510. The polymeric sealant material 504 can be the same or similar to the polymeric sealant material 404 described in connection with FIGS. 4A-4C.

[0100] The moisture barrier 520 is disposed on the polymeric sealant material 504 to inhibit moisture from reaching the polymeric sealant material 504 and the battery stack 502. The moisture barrier 520 may be shaped using any of the techniques described in connection with shaping the moisture barrier 420 described in FIGS. 4A-4C. But unlike the moisture barrier 420 described in FIGS. 4A-4C, the moisture barrier 520 forms a continuous moisture impermeable barrier that extends along at least a portion of the sidewalls 516 of the substrate 510. As shown in FIG. 5C, the moisture barrier 520 can have a raised top region 522 that is approximately parallel to the substrate 510, a transition region 528 that trends toward the substrate 510 from the raised top region 522, side edges 524 where the moisture barrier 520 is again approximately parallel to the substrate 510, and a transverse region 526 that extends along the sidewalls 516 of the substrate 510. The moisture barrier 520 terminates along the sidewalls 516 of the substrate 510 at an outer edge 529. The raised top region 522 can approximately correspond to the region spanned by the battery stack 502 on the substrate 510. The moisture barrier 520 is a continuous film or foil that is substantially impervious to moisture, and so the only moisture that can reach the polymeric sealant material 504 must enter along the sidewall 516 of the substrate 510, between the sidewall 516 and the outer edge 529.

[0101] Some implementations of the battery 500 may be fabricated so as to reduce the distance between the outer edge 529 and the sidewall 516 of the substrate 510 within fabrication limitations. Some techniques may involve compressing the transverse region 526 against the sidewalls 516 of the substrate 510. Some techniques may involve, prior to sputtering the moisture barrier 520, removing some of the polymeric sealant material 504 from the substrate 510 so as to expose a continuous ring on the sidewalls 516 of the substrate 510 that entirely surrounds the battery stack 502. The sputtered moisture barrier may then adhere directly against the sidewalls 516 of the substrate 510 in the continuous ring.

[0102] The two example arrangements of sealed thin film batteries are provided for example purposes only. Many other form factors for sealed thin film batteries are possible. For example, some embodiments may include the use of non-planar substrates, (e.g., substrates with curved or irregular surfaces). A battery stack formed on such substrates can be

surrounded by a conformal layer of polymeric sealant material and then a moisture barrier can be disposed on the polymeric sealant material so as to inhibit moisture from reaching the polymeric sealant material and the battery stack.

#### V. Example Sealed Battery Fabrication Processes

[0103] The sealed thin film batteries described herein may be formed by a variety of fabrication processes. Two example processes are described in connection with FIGS. 6A-7G. It is noted that the stages of fabrication illustrated in these figures are not drawn to scale and that the order of some stages may be interchanged in some examples and/or some stages may be omitted entirely. The sealed thin film batteries can be incorporated into body-mountable and/or implantable devices or other constrained form-factor devices, such as remote sensors, adhesives, clothing, etc. As noted further below, the sealed thin film batteries may be particularly advantageous in environments with moisture, because the moisture barrier prevents moisture from penetrating to the battery stack which could otherwise degrade the battery electrodes and/or electrolyte. For example, these batteries may be integrated into an eye-mountable device such as the eye-mountable device 210 described in FIG. 2 or another body-mountable device.

[0104] FIGS. 6A-6G describe a process in which conductive vias and mounting pads are formed on and within a substrate after the battery is already disposed on the opposite side of the substrate. FIGS. 7A-7G describe a process in which conductive vias and mounting pads are formed on and within a substrate before the battery is formed on the substrate. Variations and/or combinations of these approaches may also be used.

[0105] A. Forming Battery Stack, Followed by Vias Through Substrate

[0106] FIGS. 6A, 6B, 6C, 6D, 6E, 6F, and 6G illustrate stages of an example fabrication process for forming a sealed battery and mounting the battery in a device. The sealed battery shown in FIG. 6A includes a battery stack 620 disposed on a substrate 610. The battery stack 620 can be a thin film battery including films of anode material and cathode material separated from one another by a film of electrolyte material. For example, the battery stack 620 can be the same or similar to either of the battery stacks described in connection with FIGS. 3A and 3B. As shown in FIG. 6A, the battery stack 620 is disposed on the substrate 610 and encapsulated by a polymeric sealant material 630. The polymeric sealant material 630 can be a low temperature polymer that is applied over the battery stack 620 after fabricating the battery. The polymeric sealant material 630 may be coated over the battery stack 620 by physically applying the sealant material 630 using an applicator, by spin-coating the polymeric sealant, by spraying the polymeric sealant, and/or by other techniques. In examples where multiple batteries are formed on a common substrate and then separated by dicing or scribing the substrate, the batteries may be separated before applying the polymeric sealant material 630.

[0107] The polymeric sealant material 630 forms a conformal surrounding over the battery stack 620 that substantially encapsulates the battery stack 620 between the polymeric sealant material 630 and the substrate 610. In particular, in cases in which the battery stack 620 is electrically coupled to mounting pads situated on the opposite side of the substrate 610 (as shown in FIGS. 6D and 6E), the polymeric sealant layer 630 can fully encapsulate the battery stack 620 without penetration by lead lines that connect to the electrodes.

Instead, because vias through the substrate **610** obviate the need for terminals or lead lines on the same side of the substrate **610** as the battery stack **620**, the polymeric sealant material **630** can fully surround the battery stack **620** and provide a continuous seal against the substrate **610**, and thereby prevent contaminants from reaching the battery stack **620**.

[0108] In FIG. 6B, the polymeric sealant material **630** is covered by a moisture barrier **640**. The moisture barrier **640** may be a metallic or ceramic coating that is sputtered over the polymeric sealant material **630**. In addition to encapsulating the battery stack **620**, the polymeric sealant material **630** separates the battery stack **620** from the moisture barrier **640**. The moisture barrier **640** provides a barrier to moisture and contaminants that is substantially impervious to moisture. The moisture barrier **640** thus helps prevent moisture from reaching the polymeric sealant material **630** and the battery stack **620**. The moisture barrier **640** may therefore be helpful in preventing deleterious effects associated with moisture exposure. For example, while the polymeric sealant layer **630** may be at least partially water permeable, the moisture barrier **640** of metallic or ceramic material can be substantially impermeable to water, and therefore prevent moisture from entering the sealant material **630** through the area covered by the moisture barrier **640**.

[0109] In FIG. 6C, the moisture barrier **640** is formed over the battery stack **620**. The moisture barrier **640** may be formed by compressing the moisture barrier **640** (e.g., via a stamping process or by application of pressure). Compressing the moisture barrier can result in the outer edges of the moisture barrier **640** being depressed toward the substrate **610**, as shown in FIG. 6C. The compression of the moisture barrier **640** also increases pressure on the polymeric sealant material **630**, which may cause excess sealant material **630** to be forced under the outer edges of the moisture barrier **640**. Depressing the outer area of the moisture barrier **640** closer to the substrate **610** also decreases the exposed surface area of the polymeric sealant material **630**, which further reduces the through which moisture can reach the battery stack **620**. In addition to forming the moisture barrier **640**, compressing the moisture barrier **640** may also compress the polymeric sealant material **630** to better conform against the battery stack **620** and to help cure the sealant material **630**. The sealant material **630** can thus create a separation (buffer) between the battery stack **620** and the moisture barrier **640**, help increase the structural integrity of the assembled device, and also help prevent contaminants from reaching the battery stack **620**.

[0110] In some examples, the moisture barrier **640** may be formed along the sides of the battery stack **620** and/or substrate **610** by an isotropic deposition process or another technique in addition to, or as alternative to, compressing the moisture barrier **640**. Extending the moisture barrier **640** along the sides of the substrate **610** may create a more robust seal against moisture reaching the battery stack **620**. Moreover, some examples may not include the moisture barrier at all. For example, the battery stack **620** can be encapsulated by the polymeric sealant material **630** without anything covering the sealant material **630**. And in some examples, the moisture barrier may be formed only over the top surface of the sealant material **630** (e.g., as in the view shown in FIG. 6B).

[0111] The battery stack **620** can include a cathode terminal **622**, which may be part of a layer of patterned conductive material electrically coupled to a cathode film within the battery stack **620**. The battery stack **620** can also include an

anode terminal **624**, which may be part of a layer of patterned conductive material electrically coupled to an anode film within the battery stack **620**. In FIG. 6D, two apertures **650**, **652** are formed through the substrate **610** so as to expose the two terminals **622**, **624** from the side of the substrate **610** opposite the battery stack **620**. The aperture **650**, **652** can be formed by deep reactive ion etching, laser ablation, or another process. For example, if the apertures **650**, **652** are formed by deep reactive ion etching through the substrate **610**, the terminals **622**, **624** may be used as etch stops. The apertures **650**, **652** are aligned such that each exposes one of the electrodes of the battery (or a current collector electrically coupled to one of the electrodes). For example, the aperture **650** can be aligned to expose the cathode terminal **622** and the aperture **652** can be aligned to expose the anode terminal **624**. In some examples, the apertures **650**, **652** may be formed prior to application of the polymeric sealant material **630** and/or moisture barrier **640**.

[0112] FIG. 6E shows the apertures **650**, **652** occupied by conductive material **654**, **656** and mounting pads **658**, **660** formed on the opposite side of the substrate **610**. The conductive material **654**, **656** may be formed by depositing a seed layer along the sidewalls of the apertures **650**, **652** and electroplating a conductive material to form a continuous conductive path through the substrate **610**. The mounting pads **658**, **660** can be patterned onto non-overlapping areas of the opposite side of the substrate **610**, and each mounting pad can be electrically coupled to one of the conductive vias **654**, **656**. The conductive material **654** electrically couples the cathode terminal **622** to the conductive pad **658**; and the conductive material **656** electrically couples the anode terminal **624** to the conductive pad **660**.

[0113] FIG. 6F illustrates the assembled battery being mounted to bonding terminals **662**, **664** on another substrate **661**. The bonding terminals **662**, **664** can be electrically coupled to other electronics disposed on the substrate **661**, such as control chips, etc., via traces and interconnects patterned on the substrate **661**. An anisotropic conductive adhesive material **670**, such as anisotropic conductive paste or anisotropic conductive film, can be applied over the bonding terminals **662**, **664** and the battery can be placed over the bonding pads **662**, **664**. The anisotropic conductive material **670** can include multiple conductive particles **672** distributed within an adhesive matrix. When the battery is pressed against the substrate **661**, as shown in FIG. 6G, at least one of the conductive particles **672** is lodged between the mounting pad **658** and bonding pad **662**, and at least one other conductive particle **672** is lodged between the mounting pad **660** and the bonding pad **664**. The conductive particles **672** thereby provide electrical conductivity along the direction that the two terminals are pressed together, but not otherwise, because the conductive particles **672** remain too far apart from one another to create a conductive path.

[0114] The placement and alignment of the battery over the bonding pads **662**, **664** can be accomplished by, for example, using a tool to position the battery such that the cathode-connected mounting pad **658** is aligned with the first bonding pad **662** and the anode-connected mounting pad **660** is aligned with the mounting pad **664**. The battery can then be moved toward the bonding pads **662**, **664** to deform the anisotropic conductive material **670** and electrically couple the mounting pads **658**, **660** to the mounting pads **662**, **664**. Application of pressure and/or heat can cure the anisotropic

conductive adhesive 670 which fixes the battery in place and completes the flip-chip bonding process.

[0115] B. Forming Vias Through Substrate, Followed by Battery Stack Formation

[0116] FIGS. 7A, 7B, 7C, 7D, 7E, 7F, and 7G illustrate another example fabrication process for a sealed battery. FIG. 7A shows a substrate 710 having a first side 712 and a second side 714. A pair of holes 720, 722 (or a pair of depressions) is formed in the first side 712 of the substrate 710. The holes 720, 722 can be formed by laser ablation, deep reactive ion etching, or another technique. The holes 720, 722 can penetrate to a depth greater than the eventual thickness of the substrate 710, after thinning. Thus, once thinned, the two holes 720, 722 will extend through the entire thickness of the substrate 710. The holes 720, 722 may also extend entire through the substrate 710 (i.e., to the second side 714). The holes 720, 722 may have sidewalls that are substantially perpendicular to the first side 712 (and second side 714), which provide the shortest path through the substrate 710.

[0117] FIG. 7B shows the two holes 720, 722 after being filled by a conductive material 730, 732. For example silver, tin, gold, copper, or another metal can be electroplated onto the sidewalls to create a continuous electrical pathway from the first side 712 of the substrate 710 to the distal end of each of the holes 720, 722. FIG. 7C shows a cutaway view of the holes 720, 722 occupied by conductive material 730, 732. After filling the holes 720, 722 with conductive material 730, 732, respective top sides of the conductive material may extend beyond the plane of the first side 712 of the substrate 710 (e.g., the protrusions 731, 733). FIG. 7D shows a cutaway view after polishing the protrusions 731, 733 and/or the first side 712 of the substrate 710. Polishing removes the protrusions and creates a pair of terminals 734, 736, which are co-planar with the first side 712 of the substrate 710.

[0118] FIG. 7E shows a cutaway view after polishing the substrate 710 from the opposite side. For example, the substrate 710 may be adhered to a carrier substrate along the first side 712, and then the substrate can be thinned to create the polished surface 716. The thinning operation is performed so as to expose the conductive material 730, 732 within the two holes. The total thickness of the substrate 710, following thinning, is therefore less than the depth of the holes 720, 722. Following thinning, the conductive material 730, 732 provides electrical paths through the substrate 710 (i.e., from the first side 712 to the polished surface 716). The total thickness (“h”) of the substrate 710, after polishing, can be less than 100 micrometers. For example, the substrate thickness may be between about 20 micrometers and about 70 micrometers. For instance, the substrate 710 may initially be a silicon wafer with a thickness of about 700 micrometers, and following polishing, the substrate 710 can have a thickness of about 70 micrometers with electrical pathways through the thinned substrate by the holes.

[0119] In some examples, however, the thinning process may be omitted entirely. Instead, the substrate may be a desired thickness prior to forming the holes 720, 722, and thus the holes may instead be apertures that pass through the entire thickness of such a substrate.

[0120] As shown in FIG. 7F, a pair of mounting pads 740, 742 may be formed on the polished surface 716. For example, one of the mounting pads 740 can be arranged to be electrically coupled to the electrical material 730, and the other of the mounting pads 742 can be arranged to be electrically coupled to the electrical material 732. Thus, the mounting pad

740 is electrically coupled to the co-planar top surface 734 of the conductive material 730 and the mounting pad 742 is electrically coupled to the co-planar top surface 736 of the conductive material 732. The mounting pad 740, 742 can be formed to occupy any pattern of non-overlapping areas on the polished surface 716. For instance, the mounting pads 740, 742 may be formed such that the mounting pad 740 occupies approximately half of the polished surface 716, and the mounting pad 742 occupies the other half of the polished surface 716. Such an arrangement can maximize alignment tolerances when flip-chip mounting the battery over bonding pads on another substrate. Many other patterns are also possible. In some cases, the mounting pads 740, 742 may be omitted entirely.

[0121] FIG. 7G illustrates the completed sealed battery after a battery stack (not visible) is formed on the first side 712 of the substrate 710 and then sealed by a sealant material covered by a moisture barrier 750. As noted above, some implementations may omit or modify the moisture barrier 750. The battery stack can be patterned such that a cathode terminal thereof is aligned to overlap the top surface 734 of the conductive material 730 and an anode terminal thereof is aligned to overlap the top surface 736 of the conductive material 732. The battery shown in FIG. 7G can then be flip-chip mounted to corresponding bonding pads, similar to the description in connection with FIGS. 6F and 6G.

[0122] The sealed thin film battery can include a battery stack disposed on one side of a substrate (e.g., the first side 712 of the substrate 710), and conductive mounting pads disposed on the other side of the substrate (e.g., the mounting pads 740, 742 disposed on the polished side 716 of the substrate 710). The battery stack includes an anode film, a cathode film, and an electrolyte film that separates the anode and cathode films. One of the mounting pads can be electrically coupled to the anode, and the other mounting pad can be electrically coupled to the cathode (e.g., by respective electrical paths that pass through the substrate). The battery stack can also be covered by a polymeric sealant material that is disposed over and around the battery stack. The polymeric sealant material may form a continuous seal against the substrate that completely surrounds the battery stack and thereby encapsulates the battery stack between the sealant layer and the substrate.

[0123] As noted above, the manufacturing process described in connection with FIGS. 6A-7G may be performed so as to form multiple battery chips on a common substrate. The common substrate can then be diced to separate the individual batteries, and the separated batteries can be sealed and then integrated into various electronic devices.

[0124] Once completed, the sensor chip 640 may be incorporated in a body-mountable device. For example, the sensor chip 640 could be incorporated in an eye-mountable device similar to the eye-mountable device 210 described above by flip-chip mounting the conductive mounting pads 634, 636 to corresponding terminals on a substrate embedded in such a device (e.g., similar to the description of the sensor chip 560 in FIGS. 5C-5D). A controller can be electrically coupled to the sensor chip 640 through interconnects and can operate the sensor chip 640 by applying a voltage to the electrodes 626, 628, measuring a current through the working electrode 626, and using an antenna to wirelessly indicate the current measurement.

**[0125]** C. Example Battery Fabrication Process

**[0126]** FIG. 8 is a flowchart of an example fabrication process **800** for producing a sealed thin film battery. The process **800** may involve fabricating multiple batteries in parallel on a common substrate.

**[0127]** At block **802**, a battery stack is formed on a first side of a substrate. An example process for forming the battery stack may involve forming a cathode current collector layer on the first side of the substrate. The cathode current collector layer can occupy at least a first region of the first side of the substrate. The battery stack formation may also involve forming a cathode active layer on the cathode current collector layer. The battery stack formation may also involve forming an electrolyte layer on the cathode active layer. The battery stack formation may also involve forming an anode active layer on the electrolyte layer. The battery stack formation may also involve forming an anode current collector layer on the anode active layer. A portion of the anode current collector layer can extend beyond the anode active layer so as to be disposed on the first side of the substrate without overlapping the cathode current collector layer. As a result, the anode current collector layer can occupy at least a second region of the first side of the substrate (e.g., a region that does not overlap the first region). Thus, a portion of the first region of the substrate on which the cathode current collector is disposed can define a cathode terminal of the battery stack, and a portion of the second region of the substrate on which the anode current collector is disposed can define an anode terminal of the battery stack.

**[0128]** The battery stack formation may also include one or more annealing processes (e.g., to crystallize the cathode film). Moreover, other fabrication processes can be used to form a battery stack on the first side of the substrate, including processes in which the anode film is formed before the cathode film. Once formed, the battery stack can include, at least, an electrolyte film, a cathode film in contact with the electrolyte film, and an anode film in contact with the electrolyte film but not in contact with the cathode film. The films may be co-planar, such as occurs by layering films on top of one another over a planar substrate, but various form factors are possible in which the anode and cathode films are in contact with locally opposed surfaces of the electrolyte film. Such form factors may be selected depending on size/weight constraints in particular applications among other factors. For instance, some form factors may include curved surfaces at which the electrolyte film contacts the respective electrode films.

**[0129]** At block **804**, first and second apertures can be formed through the substrate. The apertures provide space for conductive vias that can electrically couple the anode and cathode of the battery stack to conductive mounting pads on the opposite side of the substrate. The apertures may be formed following formation of the battery, such as by an anisotropic etching process that etches through the substrate from the reverse side of the battery to expose the anode and cathode terminals of the battery. For instance, the battery stack side of the substrate may be adhered to a carrier substrate, and apertures can be etched through the substrate from the reverse side. At block **806**, the apertures are filled with conductive material. For example, silver, gold, platinum, or another metal can be electroplated over a seed layer formed on the sidewalls on the apertures. The conductive material can extend continuously through the substrate along the sidewalls of the apertures and thereby define electrical paths through

the substrate, one of which is electrically coupled to the cathode and the other of which is electrically coupled to the anode. The electrical paths through the substrate defined by the apertures filled with conductive material are also referred to herein as vias.

**[0130]** Apertures may also be formed prior to formation of the battery, such as by laser ablation and/or anisotropic etching. In such an example, the apertures can also be filled with conductive material prior to forming the battery stack on the substrate. The battery stack can then be formed such that the cathode terminal is aligned with one of the vias (i.e., conductive pathways through the substrate defined by the apertures) and the anode terminal is aligned with the other via.

**[0131]** At block **808** first and second conductive pads can be patterned on the second side of the substrate. Each of the conductive pads can be patterned over one of the vias such that the first conductive pad is electrically coupled to the cathode of the battery stack and the second conductive pad is electrically coupled to the anode of the battery stack. The two conductive terminals on the second side of the substrate can therefore be used to electrically connect to the battery formed on the first side of the substrate. Forming the apertures through the substrate, at least partially filling the apertures with conductive material, and/or forming the conductive mounting pads may involve adhering the first side of the substrate (with or without the battery formed thereon) to a carrier substrate to thereby facilitate processing on the second side of the substrate.

**[0132]** At block **810**, the substrate can be diced, which separates the individual battery cells from one another. Thus, in some examples, multiple battery cells can be simultaneously formed on a common substrate, and vias and mounting terminals for those battery cells can be formed on the opposite side of the common substrate before the substrate is diced. Of course, in cases, the common substrate may be diced earlier, and vias and/or mounting pads can be fabricated in the substrates of individual battery cells.

**[0133]** At block **812**, a polymeric sealant material can be applied over and around the battery stack of the separated battery. As noted above, the polymeric sealant material can be a low temperature polymeric formulation, such as a polymer that becomes deformable above a particular temperature (e.g., between about 100° C. and about 200° C.). For instance, the polymeric sealant material may be a polyethylene material, a polyamide material, polypropylene material, or any other thermoplastic or thermosetting polymer. The polymeric sealant material may be applied by an applicator that spreads the sealant material over and around the battery stack. The polymeric sealant material can then conform over and around the sides of the battery stack (e.g., by flowing) and create a continuous seal along the substrate that entirely surrounds the battery stack. The polymeric sealant material may also be applied by spin coating or spraying the sealant material to form a continuous layer above and around the battery stack. Because the polymeric sealant material can form a continuous layer that seals against the substrate on all sides of the battery stack, the polymeric sealant material can encapsulate the battery stack between the sealant material and the substrate.

**[0134]** At block **814**, a moisture barrier can be applied over the polymeric sealant layer. The moisture barrier can inhibit moisture from reaching the polymeric sealant material and the battery stack. In some examples, the moisture barrier can be metallic or ceramic layer that is deposited over the sealant

layer by a sputtering process. In some instances, the moisture barrier may be a flexible foil that can be applied over the polymeric sealant material, and then compressed and/or heated to cause the foil and the polymeric sealant to assume a desired shape. For example, the moisture barrier can be compressed against the substrate by applying pressure around the side edges thereof. The compression can force excess polymeric sealant material to flow out from under the cavity formed by the moisture barrier, and bring the side edges of the moisture barrier close to the substrate. The shape that can be held, at least in part, by cooling, which causes the thermoplastic polymeric sealant material to harden, which also fixes the shape of the compressed foil. In some examples, the polymeric sealant material may be formed to take a shape suitable for receiving the sputtered moisture barrier (e.g., by applying a mold to the sealant material), and then the moisture barrier can be sputtered onto the formed sealant material. Alternative techniques for applying the moisture barrier are also possible. In some instances, the moisture barrier can be deformed and/or formed so as to extend along sidewalls of the substrate on which the battery stack is disposed. The extended sides enhance the moisture resistance of the resulting device. Moreover, in some cases, the moisture barrier can be applied solely to the top surface of the moisture barrier in a layer that is substantially parallel to the plane of the substrate on which the battery stack is disposed.

**[0135]** At block 716, the battery chip can be mounted to another substrate of an electronic device. The substrate can include bonding pads that electrically coupled to electronics disposed on the substrate, such that upon mounting the battery can be used to power those electronics. In some examples, the device in which the battery is integrated may be a body-mountable device or an implantable device used to measure analyte concentrations. For example, the sensor chip can be flip-chip mounted to conductive terminals on a substrate that also includes a controller and antenna, similar to the eye-mountable and/or body-mountable sensor platforms described in connection with FIGS. 1-2, for example. The substrate for the body-mountable device may be encapsulated, partially or entirely, by biocompatible polymeric material configured to mount to a body surface or be implanted within a host. In some cases, the substrate on which the battery is flip-chip mounted may be a substrate not typically employed in battery fabrication, such as a polymeric substrate that cannot withstand the annealing temperatures and/or solvents used in battery fabrication (e.g., a parylene substrate).

**[0136]** While a variety of different mounting techniques may be employed, at least some examples may involve applying an anisotropic conductive adhesive over bonding pads on the substrate. The conductive mounting pads battery can then be aligned with the bonding pads and pressure and/or heat can be applied to force the mounting pads against the bonding pads and create an electrical connection. As it cools, the anisotropic conductive adhesive can cure, which mechanically bonds the battery in place. As a result, the battery can be securely coupled to the bonding pads.

## VI. Additional Embodiments

**[0137]** It is noted that while the various electronics platforms are described herein by way of example as an eye-mountable device or an ophthalmic device, it is noted that the disclosed systems and techniques for configurations of sealed thin film batteries can be applied in other contexts as well. For example, contexts in which measurements are obtained in-

vivo and/or from relatively small sample volumes, or are constrained to small form factors (e.g., implantable bio-sensors or other electronics platforms) may employ the battery systems and processes described herein to power devices used for such measurements. In addition, some examples may include incorporating sealed thin film batteries into articles of clothing, adhesive patches, or other small form-factor devices used for tagging and/or identifying items, obtaining measurements, and/or communicating with other devices via wireless signals. In one example, an implantable medical device may include a sealed battery encapsulated in biocompatible material and implanted within a host organism. The implantable medical device may include a circuit configured to output an indication of an analyte concentration measurement (e.g., an amperometric current reading). Reading and/or control devices can communicate with the implantable medical device to obtain measurements.

**[0138]** For example, in some embodiments, the electronics platform may include a body-mountable device, such as a tooth-mountable device. In some embodiments, the tooth-mountable device may take the form of or be similar in form to the body-mountable device 110 and/or the eye-mountable device 210. For instance, the tooth-mountable device may include a biocompatible polymeric material or a transparent polymer that is the same or similar to any of the polymeric materials or transparent polymers described herein and a substrate or a structure that is the same or similar to any of the substrates or structures described herein, although the exterior surface of the polymeric material may be formed to facilitate tooth-mounting, rather than eye-mounting. In such an arrangement, the tooth-mountable device may be configured to measure analyte concentration of a fluid (e.g., saliva) of a user wearing the tooth-mountable device. Other body mounting locations are also possible.

**[0139]** Moreover, in some embodiments, a body-mountable device may comprise a skin-mountable device. In some embodiments, the skin-mountable device may take the form of or be similar in form to the body-mountable device 110 and/or the eye-mountable device 210. For instance, the skin-mountable device may include a biocompatible polymeric material or a transparent polymer that is the same or similar to any of the polymeric materials or transparent polymers described herein and a substrate or a structure that is the same or similar to any of the substrates or structures described herein, although the exterior surface of the polymeric material may be formed to facilitate skin-mounting, rather than eye-mounting. In such an arrangement, the body-mountable device may be configured to measure analyte concentration of a fluid (e.g., perspiration, blood, etc.) of a user wearing the body-mountable device.

**[0140]** In example embodiments, the example system can include one or more processors, one or more forms of memory, one or more input devices/interfaces, one or more output devices/interfaces, and machine-readable instructions that when executed by the one or more processors cause the system to carry out the various functions, tasks, capabilities, etc., described above.

**[0141]** As noted above, in some embodiments, the disclosed techniques can be implemented by computer program instructions encoded on a non-transitory computer-readable storage media in a machine-readable format, or on other non-transitory media or articles of manufacture. Such computing systems (and non-transitory computer-readable program instructions) can be configured according to at least

some embodiments presented herein, including the processes shown and described in connection with FIG. 8.

**[0142]** The programming instructions can be, for example, computer executable and/or logic implemented instructions. In some examples, a computing device is configured to provide various operations, functions, or actions in response to the programming instructions conveyed to the computing device by one or more of the computer readable medium, the computer recordable medium, and/or the communications medium. The non-transitory computer readable medium can also be distributed among multiple data storage elements, which could be remotely located from each other. The computing device that executes some or all of the stored instructions can be a microfabrication controller, or another computing platform. Alternatively, the computing device that executes some or all of the stored instructions could be remotely located computer system, such as a server.

**[0143]** While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims.

What is claimed is:

1. A sealed battery comprising:
  - a substrate having a first side and a second side;
  - a battery stack disposed on the first side of the substrate, wherein the battery stack comprises a cathode layer, an anode layer, and an electrolyte layer, wherein a first one of the cathode layer and the anode layer is disposed on the first side of the substrate, and wherein the electrolyte layer is disposed between the cathode layer and the anode layer;
  - a polymeric sealant layer formed over and around the battery stack;
  - a first conductive pad situated on the second side of the substrate, wherein the first conductive pad is electrically coupled to the cathode layer; and
  - a second conductive pad situated on the second side of the substrate, wherein the second conductive pad is electrically coupled to the anode layer.
2. The sealed battery of claim 1, wherein the polymeric sealant layer is a substantially continuous layer that terminates along the first side of the substrate so as to fully encapsulate the battery stack between the polymeric sealant layer and the substrate.
3. The sealed battery of claim 1, wherein the polymeric sealant layer is a biocompatible material.
4. The sealed battery of claim 1, further comprising:
  - a moisture barrier disposed on the polymeric sealant layer to thereby inhibit moisture from reaching the polymeric sealant layer and the battery stack.
5. The sealed battery of claim 4, wherein the moisture barrier comprises a foil formed of a metallic or a ceramic material.
6. The sealed battery of claim 4, wherein the moisture barrier is formed to extend along sides of the sealed battery and thereby substantially enclose the battery stack between the moisture barrier and the substrate.
7. The sealed battery of claim 4, wherein the moisture barrier is separated from the battery stack by the polymeric sealant material.
8. The sealed battery of claim 1,

wherein an electrical path that couples the cathode layer and the first conductive pad includes a first via, wherein the first via comprises conductive material that at least partially occupies a first aperture through the substrate, and

wherein an electrical path that couples the anode layer and the second conductive pad includes a second via, wherein the second via comprises conductive material that at least partially occupies a second aperture through the substrate.

9. The sealed battery of claim 1, wherein the cathode layer comprises a cathode active layer and a cathode current collector layer electrically coupled to the first conductive pad, wherein the cathode current collector layer comprises conductive material disposed on the first side of the substrate, and wherein the cathode active layer is disposed on the cathode current collector layer, and

wherein the anode layer comprises an anode active layer and an anode current collector layer electrically coupled to the second conductive pad, wherein the anode active layer comprises lithium metal disposed on the electrolyte layer, and wherein the anode current collector layer comprises conductive material disposed on the anode active layer.

10. The sealed battery of claim 1, wherein the electrolyte layer comprises lithium phosphorus oxynitride.

11. The sealed battery of claim 1, wherein the sealed battery has an overall thickness defined by respective thicknesses of the substrate, the cathode layer, the electrolyte layer, the anode layer, and the polymeric sealant layer, wherein the overall thickness is less than about 80 micrometers.

12. A body-mountable device comprising:

- a polymeric material formed to have a body-mountable surface; and

- a sealed battery embedded within the polymeric material, wherein the sealed battery comprises:

- a substrate having a first side and a second side;

- a battery stack disposed on the first side of the substrate, wherein the battery stack comprises a cathode layer, an anode layer, and an electrolyte layer, wherein a first one of the cathode layer and the anode layer is disposed on the first side of the substrate, and wherein the electrolyte layer is disposed between the cathode layer and the anode layer;

- a polymeric sealant layer formed over and around the battery stack;

- a first conductive pad situated on the second side of the substrate, wherein the first conductive pad is electrically coupled to the cathode layer; and

- a second conductive pad situated on the second side of the substrate, wherein the second conductive pad is electrically coupled to the anode layer.

13. The body-mountable device of claim 12, further comprising electronics embedded in the polymeric material, wherein the electronics are configured to be powered by the sealed battery.

14. The body-mountable device of claim 13, further comprising:

- an electronics substrate at least partially embedded within the polymeric material; and

- a pair of conductive mounting pads disposed on the electronics substrate, wherein the pair of conductive mounting pads are arranged to correspond to the first and second conductive pads of the sealed battery, and

wherein the sealed battery is disposed on the pair of conductive mounting pads such that the first and second conductive pads are each aligned with a respective one of the pair of conductive mounting pads.

**15.** The body-mountable device of claim **12**, wherein the polymeric material has a concave surface and a convex surface, wherein the concave surface is configured to be removably mounted over a corneal surface and the convex surface is configured to be compatible with eyelid motion when the concave surface is so mounted.

**16.** The body-mountable device of claim **12**, wherein the polymeric sealant layer is a substantially continuous layer that terminates along the first side of the substrate so as to fully encapsulate the battery stack between the polymeric sealant layer and the substrate.

**17.** The body-mountable device of claim **12**, wherein the sealed battery further comprises:

a moisture barrier disposed on the polymeric sealant layer to thereby inhibit moisture from reaching the polymeric sealant layer and the battery stack.

**18.** The body-mountable device of claim **12**,

wherein an electrical path that couples the cathode layer and the first conductive pad includes a first via, wherein the first via comprises conductive material that at least partially occupies a first aperture through the substrate, and

wherein an electrical path that couples the anode layer and the second conductive pad includes a second via, wherein the second via comprises conductive material that at least partially occupies a second aperture through the substrate.

**19.** A method comprising:

forming a battery stack on a first side of a substrate, wherein forming the battery stack comprises: (i) forming a cathode current collector layer on the first side of the substrate, such that the cathode current collector layer occupies at least a first region of the first side of the substrate; (ii) forming a cathode active layer on the cathode current collector layer; (iii) forming an electrolyte layer on the cathode active layer; (iv) forming an anode active layer on the electrolyte layer; and (v) forming an anode current collector layer on the anode active layer, wherein a portion of the anode current collector layer extends beyond the anode active layer and is disposed on

the first side of the substrate, such that the anode current collector layer occupies at least a second region of the first side of the substrate;

forming a first aperture and a second aperture in the substrate, wherein the first aperture exposes, from the second side of the substrate, at least a portion of the cathode current collector, and wherein the second aperture exposes, from the second side of the substrate, at least a portion of the anode current collector;

filling at least a portion of each of the first and second apertures with conductive material to thereby create respective electrical pathways through the substrate;

forming, on the second side of the substrate, a first conductive pad that is electrically coupled to the conductive material within the first aperture, such that the first conductive pad is electrically coupled to the cathode current collector layer;

forming, on the second side of the substrate, a second conductive pad that is electrically coupled to the conductive material within the second aperture, such that the second conductive pad is electrically coupled to the anode current collector layer; and

applying a polymeric sealant layer over and around battery stack to thereby encapsulate the battery stack between the polymeric sealant layer and the substrate.

**20.** The method of claim **19**, further comprising:

applying a moisture barrier over the polymeric sealant layer to thereby inhibit moisture from reaching the polymeric sealant layer and the battery stack;

situating the substrate and sealed battery stack disposed thereon over a pair of conductive mounting pads arranged so as to correspond to the first and second conductive pads such that the first and second conductive pads are each aligned with a respective one of the pair of conductive mounting pads, wherein the pair of conductive mounting pads are electrically coupled to electronics configured to be powered via the pair of conductive mounting pads;

bonding the first and second conductive pads to respective ones of the pair of conductive mounting pads; and encapsulating the conductive mounting pads, the electronics electrically coupled thereto, and the substrate and battery stack disposed thereon within a polymeric material comprising a body-mountable surface.

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