



(51) International Patent Classification:

H01M 10/04 (2006.01) H01M 10/0562 (2010.01)  
H01M 10/0585 (2010.01) H01M 4/139 (2010.01)  
H01M 2/02 (2006.01) H01M 4/04 (2006.01)  
H01M 2/10 (2006.01)

(21) International Application Number:

PCT/US2017/027580

(22) International Filing Date:

14 April 2017 (14.04.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/322,415 14 April 2016 (14.04.2016) US  
15/338,969 31 October 2016 (31.10.2016) US

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(81) Designated States (unless otherwise indicated, for every  
kind of national protection available): AE, AG, AL, AM,  
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,  
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM,  
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,  
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN,  
KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA,  
MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG,  
NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS,  
RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY,  
TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN,  
ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every  
kind of regional protection available): ARIPO (BW, GH,  
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,  
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,  
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,  
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,  
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,  
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,  
GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: THIN FILM BATTERY DEVICE AND METHOD OF FORMATION

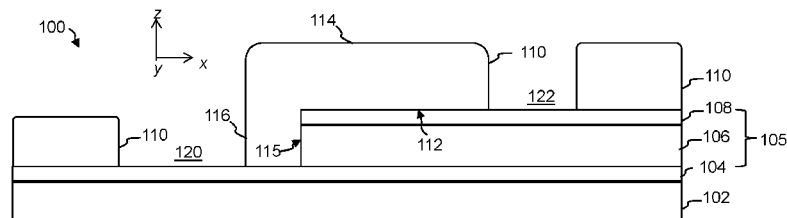
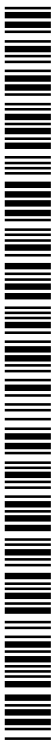


FIG. 1A

(57) Abstract: A thin film battery may include: a cathode current collector, the cathode current collector being disposed in a first plane; a device stack disposed on the cathode current collector, the device stack comprising an anode current collector, the anode current collector being disposed in a second plane, above the first plane; and a thin film encapsulant, the thin film encapsulant disposed above the device stack, wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a plurality of sides of the device stack, wherein the cathode current collector extends under the second portion of the thin film encapsulant and outside of the thin film encapsulant; and wherein the anode current collector extends under the first portion of the thin film encapsulant and outside of the thin film encapsulant.



## THIN FILM BATTERY DEVICE AND METHOD OF FORMATION

### Related Applications

[0001] This Application claims priority to U.S. provisional patent application no. 62/322,415, filed April 14, 2016, entitled "Volume Change Accommodating TFE Materials," and incorporated by reference herein in its entirety.

### Field

[0002] The present embodiments relate to thin film encapsulation (TFE) technology used to protect active devices, and more particularly to encapsulating thin film battery devices.

### Background

[0003] In the fabrication of thin film batteries, patterning of device structures remains a challenge, for forming active regions of a device, or front-end, and for forming encapsulation portions of a device, or back-end.

[0004] In particular, for seamless integration into systems incorporating thin film batteries, a large benefit is the ability to form very thin batteries. To this end, reduction of non-active materials such as encapsulation material is useful, so non-active portions of a thin film battery add minimally to the overall size of the battery. Known methods of packaging energy storage devices, such as thin film batteries, include pouching, lamination, and the like. These methods add an undesirable amount of weight and volume to the device being packaged, or encapsulated. Thin film encapsulation (TFE) approaches for protecting active components of a thin film battery offer a potentially simplified manner of encapsulation, with minimum material and volume addition to the system. Notably, TFE approaches for these types of devices, such as thin film batteries, are far more challenging for several reasons. Firstly, accommodation of volume changes is useful,

adding potential stress to a thin film encapsulant region during device operation. Secondly, a main function of the TFE is to provide good oxidant permeation barrier properties. Moreover, a TFE may be used encapsulate device structures including a larger topography variation. At the present, good TFE fabrication methods and the resulting device architectures are lacking for providing robust and consistent long-term operation of these devices.

[0005] With respect to these and other considerations the present disclosure is provided.

### **Brief Summary**

[0006] In one embodiment, a thin film battery may include a cathode current collector, the cathode current collector being disposed in a first plane; a device stack disposed on the cathode current collector, where the device stack comprises an anode current collector, where the anode current collector is disposed in a second plane, above the first plane. The thin film battery may further include a thin film encapsulant, where the thin film encapsulant is disposed above the device stack, wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a plurality of sides of the device stack. The cathode current collector may extend under the second portion of the thin film encapsulant and outside of the thin film encapsulant, and the anode current collector may extend under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

[0007] In another embodiment, a method of forming a thin film battery may include depositing a cathode current collector on a substrate in a first plane and forming a device stack on the cathode current collector, where the device stack comprises an anode current collector. The anode current collector may be disposed in a second plane above the first plane. The method may include forming a thin film encapsulant above the device stack, wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second

portion extending along a side of the device stack. The cathode current collector may extend under the device stack, under the second portion of the thin film encapsulant and outside of the thin film encapsulant. The anode current collector may extend under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

**[0008]** In another embodiment, a method of encapsulating a thin film battery may include providing an active device region on a substrate base, wherein the active device region comprises a cathode current collector and a device stack. The device stack may be disposed on a portion of the cathode current collector and include an anode current collector. The method may also include forming a thin film encapsulant above the device stack, wherein the thin film encapsulant comprises a first portion extends along a surface of the anode current collector and a second portion extending along a side of the device stack. The cathode current collector may extend under the device stack, under the second portion of the thin film encapsulant and outside of the thin film encapsulant, and the anode current collector may extend under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

### **Brief Description of the Drawings**

**[0009]** **FIG. 1A** illustrates a thin film battery according to various embodiments of the disclosure;

**[0010]** **FIG. 1B** provides one embodiment of a thin film battery, arranged according to embodiments of the disclosure;

**[0011]** **FIGs. 2A-2J** illustrates a cross-sectional view of a thin film battery at various stages of assembly; and

**[0012]** **FIG. 3** shows an exemplary process flow according to embodiments of the disclosure.

### **Detailed Description**

**[0013]** The present embodiments will now be described more fully hereinafter with reference to the accompanying drawings, where some embodiments are shown. The subject matter of the present disclosure may be embodied in many different forms and are not to be construed as limited to the embodiments set forth herein. These embodiments are provided so this disclosure will be thorough and complete, and will fully convey the scope of the subject matter to those skilled in the art. In the drawings, like numbers refer to like elements throughout.

**[0014]** The present embodiments are related to thin film encapsulant structures and methods, where the thin film encapsulant is used to minimize ambient exposure of active devices. The present embodiments provide novel structures and materials combinations for thin film devices encapsulated using thin film encapsulation.

**[0015]** Examples of active devices include electrochemical devices include electrochromic windows and thin film batteries wherein the active component materials are highly sensitive/reactive to moisture or other ambient materials. To this end, known electrochemical devices such as thin film batteries may be provided with encapsulation to protect the active component materials.

**[0016]** In various embodiments, a thin film device such as a thin film battery and techniques for forming a thin film battery are provided with a novel architecture including an encapsulant material. The thin film battery may include a layer stack composed of active layers, as well as the thin film encapsulant, where the thin film encapsulate also constitutes a multilayer structure.

[0017] In various embodiments novel combinations of thin film deposition and patterning operations is established, for formation of an active device region, a thin film encapsulant, or a combination of active device region and thin film encapsulant.

[0018] According to various embodiments, techniques are provided for forming thin film batteries exhibiting an improvement in the structure, the ease of manufacturing, performance, or a combination of these factors, as compared to known thin film batteries. Various considerations may affect the design of a thin film battery. A non-exhaustive list of factors includes the ability of the battery to accommodate local volume changes within specific regions of the thin film battery taking place during operation of a battery; protection from oxidative permeation; and ability to form a device accounting for large variations in topography. Further factors include the ability to limit the non-active material in a thin film battery to an acceptable level; the ability to form a thin film battery having an acceptable portion of non-active material within the device regions; and ability to manufacture a thin film battery using cost-effective techniques. In particular embodiments disclosed herein, the formation of thin film encapsulation is integrated with the formation of active device regions of a thin film battery in a novel manner enabling a more robust architecture for operation and stability of the thin film battery.

[0019] **FIG. 1A** illustrates a thin film battery 100 according to various embodiments of the disclosure. The thin film battery 100 may include a substrate 102. In some embodiments, the substrate 102 may be considered a substrate base forming a part of the thin film battery 100 or may serve as a support for the thin film battery. The substrate 102 may be an insulator, semiconductor, or a conductor, depending upon the targeted electrical properties of the exterior surfaces. More specifically, the substrate 102 may be made from a ceramic, metal or glass, such as, for example, aluminum oxide, silicate glass, or even aluminum or steel, depending on the application.

[0020] As shown in FIG. 1A, the thin film battery 100 may include a cathode current collector 104, where the cathode current collector 104 is disposed as a layer on the substrate 102 in a first plane (parallel to the X-Y plane of the Cartesian coordinate system shown). The cathode current collector 104 may be a known cathode current collector such as a metal or metal alloy. The thin film battery 100 may include a device stack 105, where the device stack 105 is disposed on the cathode current collector 104. The device stack 105 may include an anode current collector 108, where the anode current collector 108 is disposed in a non-coplanar configuration in a second plane, above the first plane of the cathode current collector 104. The device stack 105 may also include a portion 106 composed of additional components as in known thin film batteries, including cathode, electrolyte, and anode in some cases. The thin film battery 100 may further include a thin film encapsulant 110 disposed above the device stack 105. The thin film encapsulant 110 may serve to encapsulate at least a portion of the device stack 105 to protect the thin film battery 100. As detailed below, in various embodiments, the thin film encapsulant 110 may include a plurality of layers. As shown in FIG. 1A, the thin film encapsulant 110 may be patterned to define various regions where no thin film encapsulant material is present. For example, in region 120 no thin film encapsulant material is present, providing a region where a contact to the thin film battery 100 may be formed. While not shown, contact material, such as a metal, such as silver, may be provided in the region 120. This contact material provides a conductive path for forming an external contact to the cathode side of the thin film battery 100. Additionally, in region 122 no thin film encapsulant material is present, providing a region where a contact to the thin film battery 100 may be formed. This contact provides a conductive path for forming an external contact to the anode side of the thin film battery 100.

**[0021]** In various embodiments, the thin film encapsulant 110 may be arranged as a thin film encapsulant including a first portion extending along a surface of the anode current collector 108 and a second portion extending along a side of the device stack 105. In particular, as shown in FIG. 1A, the thin film encapsulant 110 may include a portion 114 extending over the surface 112 of the anode current collector 108, and a portion 116 extending along a side 115 of the device stack 105. As such, the thin film encapsulant 110 provides at least partial encapsulation of the device stack 105. For example, while the side 115 is shown as encapsulated, encapsulation also extends to the right side of device stack 105 (not shown).

**[0022]** Turning now to FIG. 1B, there is shown a thin film battery 150, where the thin film battery 150 may be a variant of the thin film battery 100. As shown, the thin film battery 150 may include a device stack 105, including a cathode 152, where the cathode 152 is disposed on the cathode current collector 104; and a solid state electrolyte 154, where the solid state electrolyte 154 is disposed on the cathode 152 and under the anode current collector 108. In this variant, the thin film encapsulant 110 includes a plurality of layers as shown. In particular, the thin film encapsulant 110 may include a layer stack including a layer 160, a layer 162, a layer 164, a layer 166, a layer 168, and a layer 170. These layers in the thin film encapsulant 110 may serve multiple functions, including protecting the device stack 105 from being attacked by oxygen, water, or other species tending to damage the thin film battery 100. To this end, the thin film encapsulant 110 may encapsulate the cathode 152, the solid state electrolyte 154, and anode current collector 108 on the side 115 (see FIG. 1A) of the device stack 105, as well as to the right side (not shown) of the cathode 152, the solid state electrolyte 154, and anode current collector 108. Accordingly, the thin film encapsulant 110 includes a first portion extending along a surface of the anode current

collector 108 and a second portion extending along a side or sides of the device stack 105, including the side 115 and other side to the right (not shown).

**[0023]** The thin film encapsulant 110 may further act to accommodate volume changes occurring in the device stack 105 when the thin film battery 100 is charged and discharged. For example, in embodiments where the thin film battery is a lithium battery, the cathode 152 may be a  $\text{LiCoO}_2$  material including lithium, where the lithium diffuses back and forth between the cathode 152 and the anode current collector 108 during charging and discharging. The lithium may diffuse through the solid state electrolyte 154, where the solid state electrolyte 154 may be a known lithium phosphorous oxynitride (LiPON) material conducting the lithium between the cathode 152 and an anode region (not specifically shown) in the device stack 105. As such the lithium may tend to accumulate in a layer in the anode region during charging or to evacuate the anode region during discharging, where an effective layer thickness in the anode region may change by several micrometers or more during the charging and discharging.

**[0024]** At least one of the layers of the thin film encapsulant 110 in the embodiment of FIG. 1B may be a soft and pliable polymer layer useful for accommodating such volume changes in the device stack 105. In specific embodiments, the term "polymer layer" may refer to just one polymer layer or to a polymer layer stack including multiple sub-layers of different polymers, where at least one sub-layer is soft and pliable. A soft and pliable polymer layer, either arranged as just one layer, or as a layer stack of sub-layers, may be characterized by a relatively lower elastic modulus, relatively high elongation to break, and related properties. Examples of materials having low elastic modulus include silicone: hardness of ~ A40 Shore A, Young's Modulus of ~ 0.9 Kpsi or ~ 6.2 MPa; Parylene-C: hardness of ~ Rockwell R80, Young's Modulus of ~ 400 Kpsi or ~ 2.8 GPa; KMPR: Young's Modulus of ~ 1015 Kpsi or ~ 7.0 GPa; polyimide: hardness of D87 Shore

D, Young's Modulus of ~ 2500 Kpsi or ~ 17.2 GPa. Examples of a relatively larger elongation to break include: silicone, 100 to 210%; Parylene-C, 200%; polyimide, 72%; acrylic, 2.0 to 5.5%; epoxy, 3 to 6%.

**[0025]** More particularly, as used herein, a "soft and pliable" material may refer to a material having an elastic (Young's) modulus less than 20 GPa, for example, while a "rigid material." such as a rigid metal layer or rigid dielectric layer, may have an elastic modulus greater than 20 GPa. Other characteristic properties associated with a soft and pliable material include a relatively high elongation to break, such as 70% or greater for at least one polymer layer of the thin film encapsulant. In some examples, such as silicone, a soft and pliable material may have an elongation to break up to 200% or greater.

**[0026]** As an example, the layer 160 may be a soft and pliable polymer, while the layer 162 may be a rigid material, such as a rigid metal or a rigid dielectric, such as silicon nitride. The layer 162 may serve the function of preventing oxygen and water diffusion into the device stack 105. The sequence layers of a polymer layer and a rigid dielectric layer may be repeated through the thin film encapsulant 110. In other words, the thin film encapsulant 110 may include at least one dyad, wherein a given dyad includes a soft and pliable polymer layer, and a rigid dielectric layer disposed adjacent the polymer layer. In particular embodiments, the layer 164 may be a polymer layer such as a soft and pliable polymer layer, the layer 166 a rigid dielectric layer or rigid metal layer, the layer 168 a soft and pliable polymer layer, and the layer 170 a rigid dielectric layer or rigid metal layer. While the thin film encapsulant 110 of FIG. 1B includes four dyads, in other embodiments a thin film encapsulant may include a greater number or a lesser number of dyads.

**[0027]** As further illustrated in FIG. 1B, the thin film encapsulant 110 may be arranged as a thin film encapsulant where a polymer layer, and a rigid dielectric layer or a rigid metal layer,

extend in a non-planar fashion on the device stack 105. In particular the multiple soft and pliable polymer layers and rigid dielectric layers of thin film encapsulant 110 may be arranged along the surface 112 (see FIG. 1A) of the anode current collector 108. These layers may lie parallel to the X-Y plane (horizontally) in the portion 114, while these same layers extend more vertically along the side of the device stack 105 in the portion 116, as shown.

**[0028]** FIGs. 2A-2J illustrates a cross-sectional view of a thin film battery at various stages of assembly. In this example, the final structure 220 illustrated at FIG. 2J may represent a portion of the thin film battery 150 of FIG. 1B. A particular feature of the embodiments reflected in FIGs. 2A-2J is a method providing the integration of a thin film encapsulant with the formation of a non-coplanar configuration of cathode current collector and anode current collector layers. The flow of operations shown in FIGs. 2A-2J has the advantage of providing a straightforward process flow while utilizing substrate area in an efficient manner.

**[0029]** Turning now to FIG. 2A, there is shown an instance where a series of layers are disposed on the substrate 102. In particular, the cathode current collector 104, cathode layer 152A, solid state electrolyte layer 154A, and anode current collector layer 108A are formed in a layer sequence above the substrate 102. The cathode current collector 104, cathode layer 152A, solid state electrolyte layer 154A, and anode current collector layer 108A may be deposited in a sequence of blanket depositions in various embodiments. Other known operations for forming an active device region of a thin film battery may be performed, such as annealing the substrate after the depositing the cathode, and before depositing the solid state electrolyte. Additionally, in some variants, a distinct anode layer (not shown) may be formed by depositing a lithium anode layer after the depositing the solid state electrolyte layer 154A and before the depositing the anode current collector layer 108A.

[0030] In some embodiments, the individual layers may be deposited using any combination of physical vapor deposition, chemical vapor deposition, and liquid deposition techniques. The layer thickness of these layers may be in accordance with thicknesses for known thin film batteries.

[0031] Turning now to **FIG. 2B** there is shown a subsequent instance where the layers shown in FIG. 2A, save the cathode current collector 104, have been patterned to form a device stack 105. In various embodiments, the structure of FIG. 2B may be formed by patterning the cathode layer 152A, the solid state electrolyte layer 154A, and the anode current collector layer 108A to form the device stack 105 and to expose the cathode current collector 104, forming the exposed surface 124, in a first region 202. In some embodiments, the device stack 105 may be formed by applying a maskless etching process, such as laser etching to at least one layer of the device stack 105. In other embodiments, at least one of the layers of the device stack 105 may be patterned using masking and etching as in known processes. The formation of the device stack 105 may take place using any combination of maskless and masked patterning processes. In various embodiments the thickness of the device stack 105 may range from 15 micrometers to 60 micrometers. The embodiments are not limited in this context. In various embodiments, the patterning of the device stack 105 may be accomplished by using laser ablation or other laser processing as detailed below, with respect to patterning of a thin film encapsulant. In brief, select portions of a given layer of the device stack 105 may be etched using laser ablation where a laser is rastered over the select portion of the layer to be etched for a given time and number of repetitions to achieve a target etch depth. Etching may proceed from the top layer down, which layer may be the anode current collector 108, where at the end of the ablation process, the laser intensity is lowered to a level just below the ablation threshold for the cathode current collector

104. This lowering of the laser intensity allows removal of the remaining amount of the cathode 152 in the select portion being etched, while not etching the cathode current collector 104.

[0032] In various embodiments, the formation of a thin film encapsulant such as the thin film encapsulant 110 may take place in a series of operations, as detailed in FIG. 2C to FIG. 2J. Turning now to **FIG. 2C** there is shown a subsequent instance involving the depositing of an initial polymer layer, shown as layer 160, in blanket form directly on the anode current collector 160 as well as on the first region 202 of the cathode current collector 104. In particular embodiments, the initial polymer layer, layer 160, may be a soft and pliable polymer. The blanket deposition of the layer 160 may be performed in a manner where the layer 160 provides a conformal coat, so the side 115 of the device stack 105 is also coated. As such, the layer 160 may extend horizontally in some regions and vertically in other regions.

[0033] In various embodiments, the layer 160 may include a plurality of sub-layers, where different sub-layers are arranged to favor conformality or planarization effects. The choice of materials and deposition methods for different sub-layers may be tailored to induce either planarization or conformality. For example, a first sub-layer may be more conformal to promote sidewall coverage in a given topography – such as Parylene. The second sub-layer may be more planarizing for better next-layer deposition, e.g., spin/dip coating method. The use of multiple sub-layers within a layer 160, as well as the use of additional layers in a thin film encapsulant (*see* layer 162 as discussed below), may generate additional benefits including improved adhesion and mechanical properties, as well as limiting reactions in active regions of a thin film battery.

[0034] Turning now to **FIG. 2D** there is shown a subsequent instance where after depositing the initial polymer layer, patterning the initial polymer layer, layer 160, is performed to form a patterned polymer layer over a patterned device stack, in other words, over the device stack

105. This patterning leaves the layer 160 along the side 115 of the device stack 105 and exposes the cathode current collector 104 in a second region 204, where the second region 204 is disposed in the first region 202. In various embodiments, the patterning the layer 160 may be performed by a masked patterning process or by a maskless patterning process. In either a maskless or masked patterning process, the second region 204 is located within the first region 202.

**[0035]** An advantage of using a maskless patterning process, such as laser etching, is the avoidance of complexity and costs associated with known masked patterning processes involving lithography and dry etching or wet etching. In this manner the complexities of lithography and etching, the consumable costs, and device effects are eliminated. In addition, laser based patterning allows device shape/design to be software recipe based, not depending upon physical masks, facilitating more rapid, flexible and simpler design changes.

**[0036]** In various embodiments, laser patterning may be accomplished primarily in two ways: using diffractive optics employing relatively high power to spread the laser beam over larger areas. This approach may be especially suitable for simple, easily repeated patterns not having fine pattern details. Another type of laser patterning especially useful for patterning thin film batteries according to the present embodiment is direct laser ablation using a rastering approach. Simple and advanced galvanometer based scanners may raster the laser beam to form more complex patterns, and are less limited by feature size and dimensions. To minimize patterning times, high repetition rate lasers (>1 MHz) may be used in combination with polygon mirrors to accomplish high volume production rates.

**[0037]** Pulse durations of picosecond and femtoseconds have been shown to be effective for thin film ablation. The use of radiation wavelengths in the ultraviolet (UV) range, green visible range, as well as infrared range, including wavelengths ranging from 157 nm to 1024 nm, may be

effectively employed for patterning via laser ablation the layers of thin film batteries of the present embodiments, including polymer layers, rigid dielectric layers, and metal layers. While thin film encapsulant materials are often transparent or semi-transparent, usable wavelengths may be more appropriate in the UV or green visible range. Most of the aforementioned short pulse lasers are DPSS (Diode pumped solid state) while some fiber based lasers are also contemplated for use in embodiments of the disclosure.

**[0038]** In various embodiments, the material of layer 160, such as a flexible polymer material, and the thickness of the layer 160 may be arranged to provide benefits, such as accommodating deformation in the device stack 105 taking place due to transport of lithium during charging and discharging of a thin film battery to be formed. Turning now to **FIG. 2E** and **FIG. 2F**, there are shown subsequent operations where a patterned dyad process is performed after the formation of the patterned initial polymer layer as exemplified by **FIG. 2D**. A patterned dyad process may involve depositing a blanket dyad composed of a rigid dielectric layer and a polymer layer on device stack 105 and on the cathode current collector 104. The patterned dyad process may further involve patterning the blanket dyad to form a patterned thin film encapsulant over the patterned device stack.

**[0039]** In the particular example of **FIG. 2E**, the first part of the patterned dyad process involves depositing the layer 162, where the layer 162 may be a rigid dielectric layer, and depositing the layer 164, where the layer 164 may be a polymer layer such as a soft and pliable polymer layer. The layer 162 and layer 164 may be deposited as blanket layers, using a physical vapor deposition method, chemical vapor deposition method, liquid deposition method, other method, or any combination of these methods.

**[0040]** Turning now to **FIG. 2F** there is shown the subsequent instance where patterning

of the layer 162 and layer 164 has been performed. As illustrated the patterning has the effect to expose the cathode current collector 104 in a new region, shown as the region 206, where the new region is disposed in the second region 204. Again, the region 206 may be smaller than the second region 204. The patterning the layer 162 and the layer 164 may be performed by a masked etching process or by a maskless etching process. In either a maskless or masked patterning process, the second region 204 is located within the first region 202. According to various embodiments, the patterning of the layer 162 and layer 164 may be conducted just one patterning process where just one etch operation takes place, and just one mask formation process is used in the case of a masked patterning operation. Alternatively, the patterning of the layer 162 and layer 164 may employ just one mask, while a plurality of etch operations are performed, such as two different etch processes to etch the two different layers. Additionally, the patterning of the layer 162 and layer 164 may involve using a masked patterning process for one layer and a maskless patterning process for the other layer. The embodiments are not limited in this context.

**[0041]** After performing a patterned dyad process, this process may be repeated at least one time to generate a plurality of patterned dyads, according to some embodiments of the disclosure. Turning now to **FIG. 2G** and **FIG. 2H**, there are shown subsequent operations where a second patterned dyad process is performed after the instance of FIG. 2F. The second patterned dyad process involves the deposition and patterning of the layer 166 and the layer 168, in accordance with the deposition and patterning described above with respect to FIGs. 2E and 2F.

**[0042]** In the particular example of FIG. 2G, the first part of the second patterned dyad process involves depositing the layer 166, where the layer 166 may be a rigid dielectric layer, and depositing the layer 168, where the layer 168 may be a polymer layer such as a soft and pliable polymer layer. The layer 166 and layer 168 may be deposited as blanket layers, as described above

with respect to FIG. 2E.

[0043] Turning now to FIG. 2H there is shown the subsequent instance where patterning of the layer 166 and layer 168 has been performed. As illustrated the patterning has the effect to expose the cathode current collector 104 in a new region, shown as the region 208, where the new region is disposed in the second region 204. Again, the region 208 may be smaller than the second region 204. The patterning the layer 162 and the layer 164 may be performed as described above with respect to FIG. 2F.

[0044] Turning now to FIG. 2I and FIG. 2J, there is shown the operations performed after the instance of FIG. 2H where a final layer, such as a rigid dielectric layer may be deposited and patterned. Turning first to **FIG. 2I**, there is shown the instance after the depositing of a layer 170, where the layer 170 may be a rigid dielectric layer. The layer 170 may be deposited in blanket form by physical vapor deposition, chemical vapor deposition, and liquid deposition techniques.

[0045] In various embodiments, the formation of a thin film encapsulant such as the thin film encapsulant 110 may take place in a series of operations, as detailed in FIG. 2C to FIG. 2J. Turning now to **FIG. 2I** there is shown a subsequent instance involving the depositing of the final rigid dielectric layer, shown as layer 170, in blanket form.

[0046] Turning now to **FIG. 2J** there is shown a subsequent instance where after depositing the final rigid dielectric layer, patterning the final rigid dielectric layer, layer 170, is performed. As illustrated the patterning has the effect to expose the cathode current collector 104 in a new region, shown as the region 210, where the new region is disposed in the second region 204. Again, the region 210 may be smaller than the second region 204.

[0047] While not explicitly shown in FIGs. 2A-2J, during the respective patterning operations, such as those depicted in FIG. 2D, FIG. 2F, FIG. 2H, and FIG. 2J, the thin film battery

may be patterned in other parts of the thin film battery. For example, returning to FIG. 1B, patterning may be performed in the region 122 during the operations of FIG. 2D, FIG. 2F, FIG. 2H, and 2J, to form the structure shown, exposing a surface 126 of the anode current collector 108. Notably, in various embodiments, the patterning operations generally shown in FIGs. 2B-2J may be carried out in their entirety using laser etching, such as laser ablation. By using laser ablation for the sequence of operations shown, a thin film battery may be formed in a streamlined manner, avoiding cost and processing complexity associated with known lithographic and etching processes.

**[0048]** In addition, and in accordance with embodiments of the disclosure, a contacting metal may be deposited on the region 210 to form a cathode contact, as well as in the region 122 as shown in FIG. 1B.

**[0049]** Turning now to **FIG. 3** there is shown an exemplary process flow 300 according to embodiments of the disclosure. At block 302 a cathode current collector is deposited on a substrate in a first plane. At block 304, a device stack is formed on the cathode current collector, where the device stack includes an anode current collector disposed in a second plane above the first plane. In various embodiments the device stack may be formed by depositing a series of layers and patterning the layers to form a patterned device stack. The patterned device stack may generate exposed regions of the cathode current collector, for example. At block 306, a thin film encapsulant is formed above the device stack. In some embodiments, the thin film encapsulant may be formed in a series of blanket depositions covering the patterned device stack and exposed regions, such as regions of the cathode current collector and anode current collector. The thin film encapsulant may be patterned so as to form regions above the cathode current collector and the anode current collector. In particular embodiments, the thin film encapsulant may be patterned to

form a thin film encapsulant, wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a side of the device stack. At the same time the cathode current collector may extend under the device stack, under the second portion of the thin film encapsulant and outside of the thin film encapsulant, and the anode current collector may extend under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

**[0050]** There are multiple advantages provided by the present embodiments, including the ability to protect a device stack of a thin film battery while maximizing available substrate area, and the additional advantage of the ability to encapsulate a device stack in a manner accommodating changes in volume during operation of the thin film battery.

**[0051]** The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments of and modifications to the present disclosure, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Furthermore, the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose, while those of ordinary skill in the art will recognize the usefulness is not limited thereto and the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Thus, the claims set forth below are to be construed in view of the full breadth and spirit of the present disclosure as described herein.

**What is claimed is:**

1. A thin film battery, comprising:
  - a cathode current collector, the cathode current collector being disposed in a first plane;
  - a device stack disposed on the cathode current collector, the device stack comprising an anode current collector, the anode current collector being disposed in a second plane, above the first plane; and
  - a thin film encapsulant, the thin film encapsulant disposed above the device stack, wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a plurality of sides of the device stack, wherein the cathode current collector extends under the second portion of the thin film encapsulant and outside of the thin film encapsulant, and wherein the anode current collector extends under the first portion of the thin film encapsulant and outside of the thin film encapsulant.
2. The thin film battery of claim 1, wherein the thin film encapsulant comprises at least one dyad, wherein a dyad of the at least one dyad comprises:
  - a soft and pliable polymer layer; and
  - a rigid dielectric layer or a rigid metal layer, the soft and pliable polymer layer being disposed adjacent the rigid dielectric layer or rigid metal layer.
3. The thin film battery of claim 1, wherein the device stack further comprises:
  - a cathode, the cathode being disposed on the cathode current collector; and

a solid state electrolyte, the solid state electrolyte disposed on the cathode and under the anode current collector.

4. The thin film battery of claim 3, wherein the thin film encapsulant encapsulates the cathode, the solid state electrolyte and the anode current collector on a side of the device stack.

5. The thin film battery of claim 4, wherein the thin film encapsulant comprises a polymer layer and a rigid dielectric layer, the rigid dielectric layer being disposed adjacent the polymer layer, wherein the polymer layer and the rigid dielectric layer extend in a non-planar fashion along the surface of the anode current collector and along the side of the device stack.

6. The thin film battery of claim 2, wherein the thin film encapsulant comprises a plurality of dyads, wherein the thin film encapsulant further comprises a third region, wherein in the third region, in at least one dyad of the plurality of dyads the soft and pliable polymer layer and the rigid dielectric layer extend in a non-planar fashion above the surface of the anode current collector.

7. The thin film battery of claim 1 further comprising a substrate base, the substrate base disposed adjacent the cathode current collector.

8. A method of forming a thin film battery, comprising:  
depositing a cathode current collector on a substrate in a first plane;  
forming a device stack on the cathode current collector, the device stack comprising an anode current collector, the anode current collector being disposed in a second plane above the

first plane; and

forming a thin film encapsulant above the device stack,

wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a side of the device stack,

wherein the cathode current collector extends under the device stack, under the second portion of the thin film encapsulant and outside of the thin film encapsulant, and

wherein the anode current collector extends under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

9. The method of claim 8, wherein the forming the device stack comprises:

depositing a cathode layer on the cathode current collector;

annealing the substrate after the depositing the cathode layer;

depositing a solid state electrolyte layer on the cathode layer;

depositing the anode current collector on the solid state electrolyte layer; and

before the forming the thin film encapsulant, patterning the cathode layer, the solid state electrolyte layer, and the anode current collector to form the device stack and to expose the cathode current collector in a first region.

10. The method of claim 9, wherein the forming the thin film encapsulant comprises forming a plurality of patterned dyads on the anode current collector, wherein a given patterned dyad of the plurality of patterned dyads comprises a soft and pliable polymer layer and a rigid dielectric layer.

11. The method of claim 9, wherein the forming the thin film encapsulant comprises:  
depositing a plurality of layers, wherein at least one layer comprises a soft and pliable polymer and at least one layer comprises a rigid dielectric layer; and  
etching the plurality of layers using a plurality of etch operations.
12. The method of claim 9, wherein the forming the thin film encapsulant comprises depositing an initial polymer layer in blanket form directly on the anode current collector and on the first region of the cathode current collector, wherein the initial polymer layer comprises a soft and pliable polymer.
13. The method of claim 12, further comprising: after the depositing the initial polymer layer: patterning the initial polymer layer to form a patterned polymer layer over the device stack and to expose the cathode current collector in a second region, the second region being disposed in the first region.
14. A method of encapsulating a thin film battery, comprising:  
providing an active device region on a substrate base, wherein the active device region comprises a cathode current collector and a device stack, the device stack being disposed on a portion of the cathode current collector and including an anode current collector; and  
forming a thin film encapsulant above the device stack,  
wherein the thin film encapsulant comprises a first portion extending along a surface of the anode current collector and a second portion extending along a side of the device stack,  
wherein the cathode current collector extends under the device stack, under the second

portion of the thin film encapsulant and outside of the thin film encapsulant, and

wherein the anode current collector extends under the first portion of the thin film encapsulant and outside of the thin film encapsulant.

15. The method of claim 14, wherein the active device region further comprises a cathode and a solid state electrolyte, wherein the providing the active device region comprises:

depositing in blanket form the cathode current collector, the cathode, the solid state electrolyte, and the anode current collector; and

patterning the anode current collector, the solid state electrolyte, and the cathode, wherein a portion of the cathode current collector is exposed.

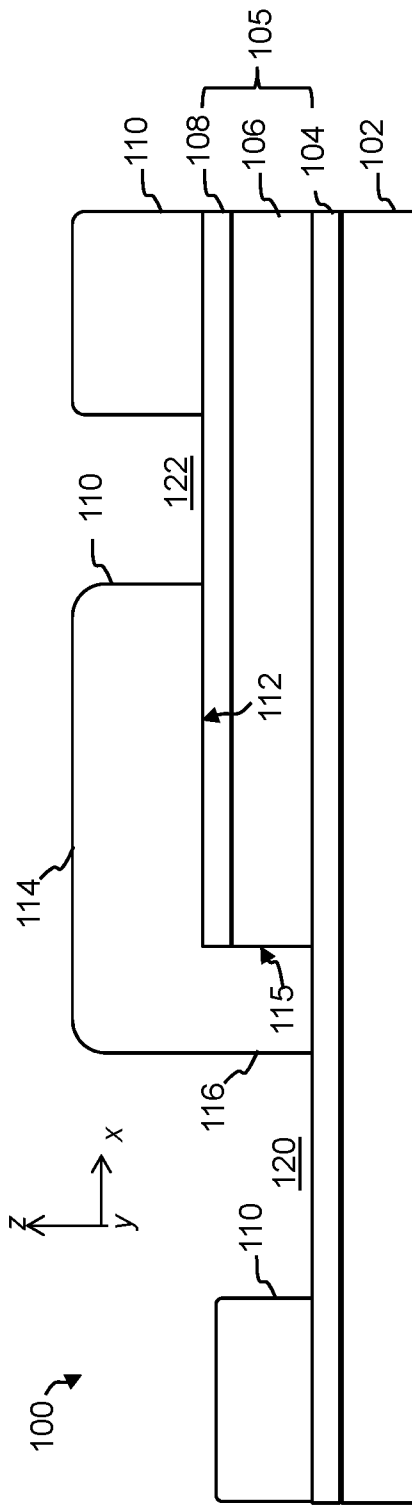


FIG. 1A

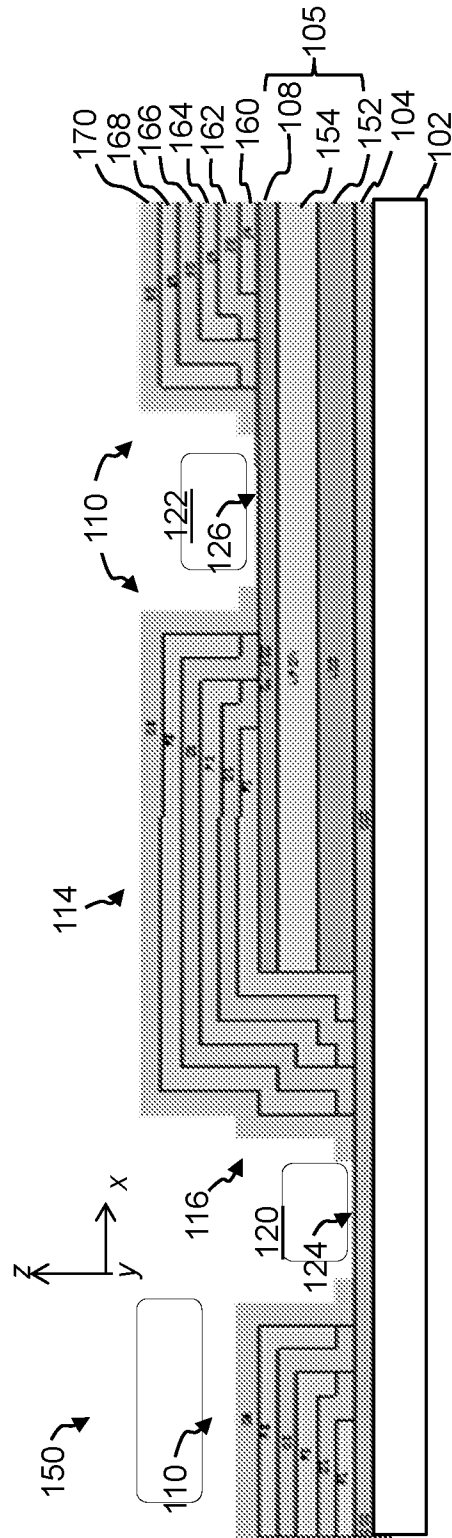
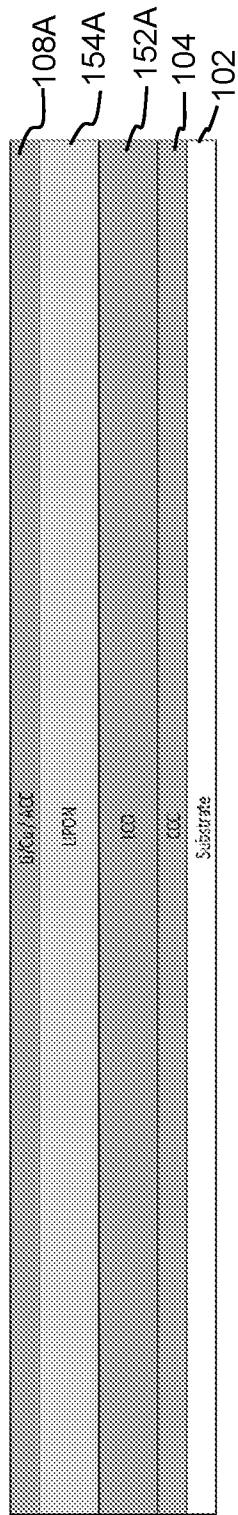
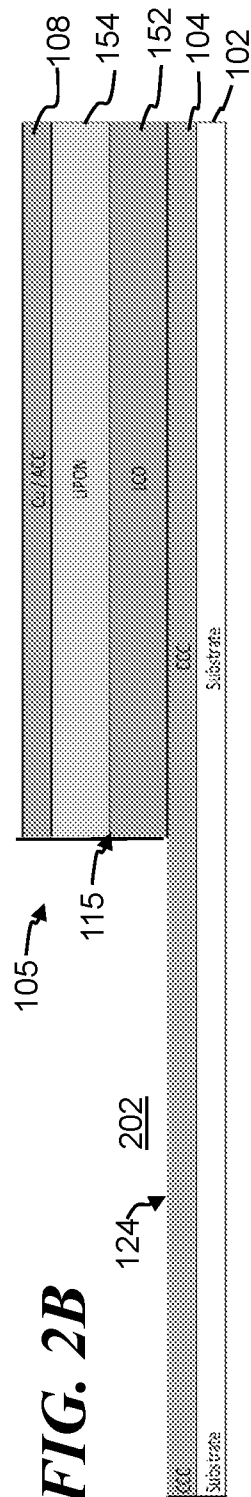


FIG. 1B

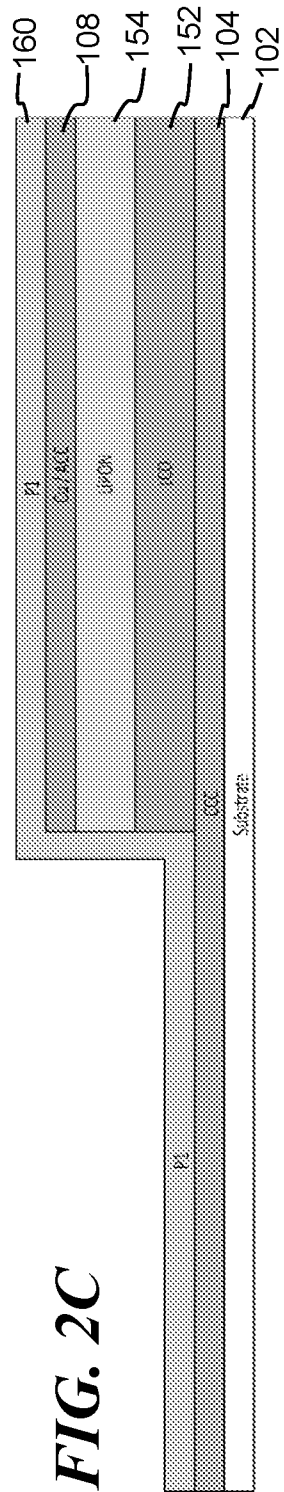
**FIG. 2A**



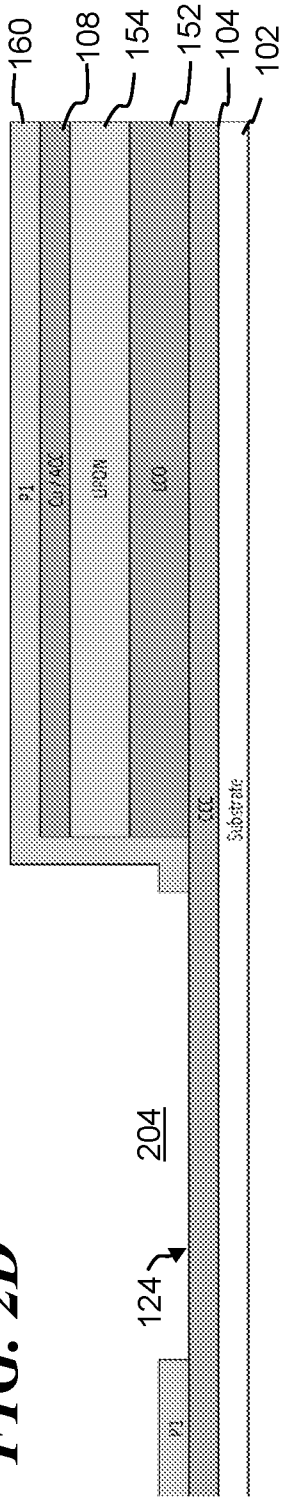
**FIG. 2B**



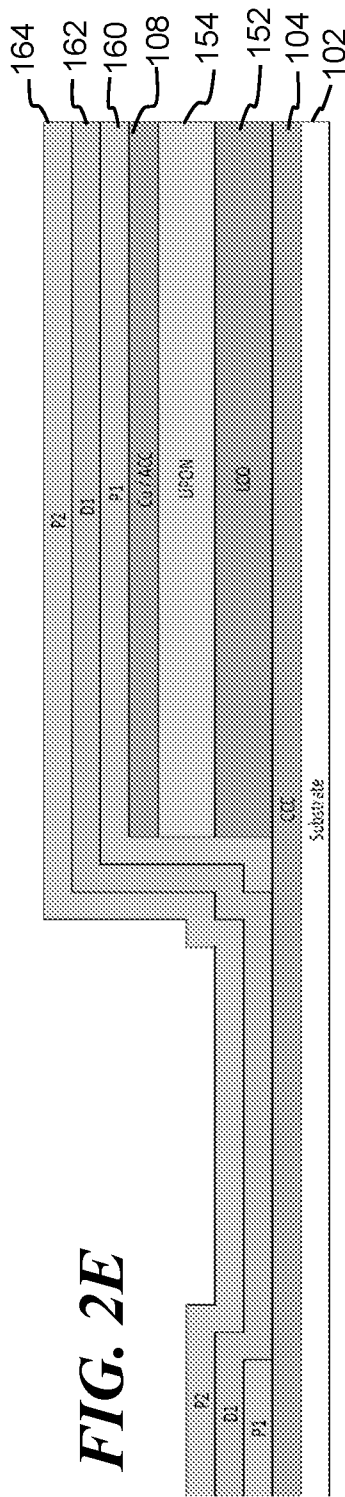
**FIG. 2C**



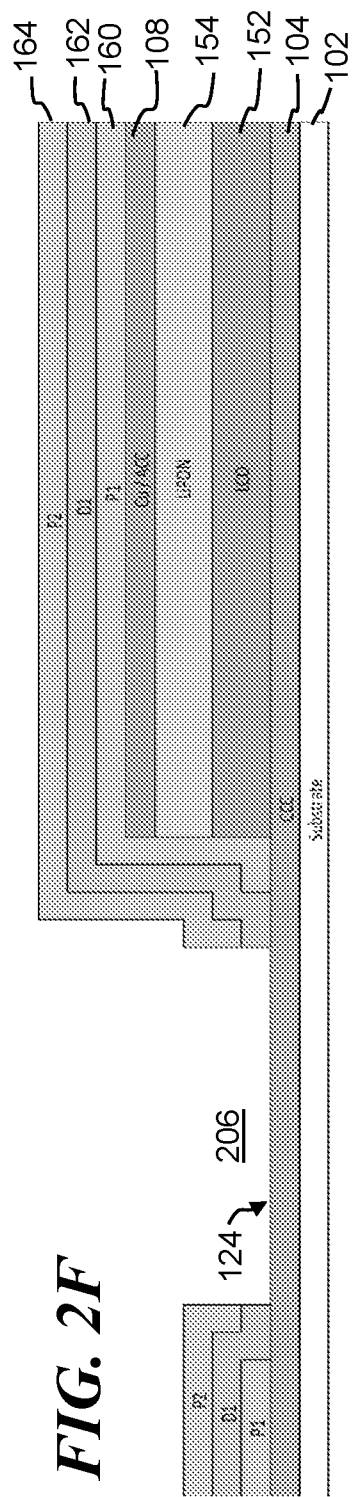
**FIG. 2D**



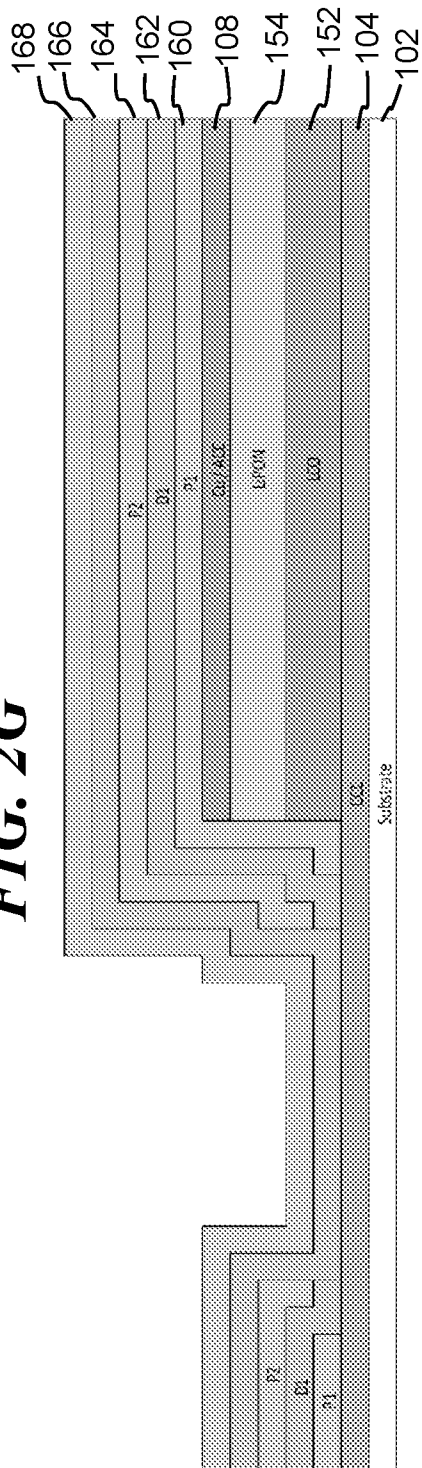
**FIG. 2E**



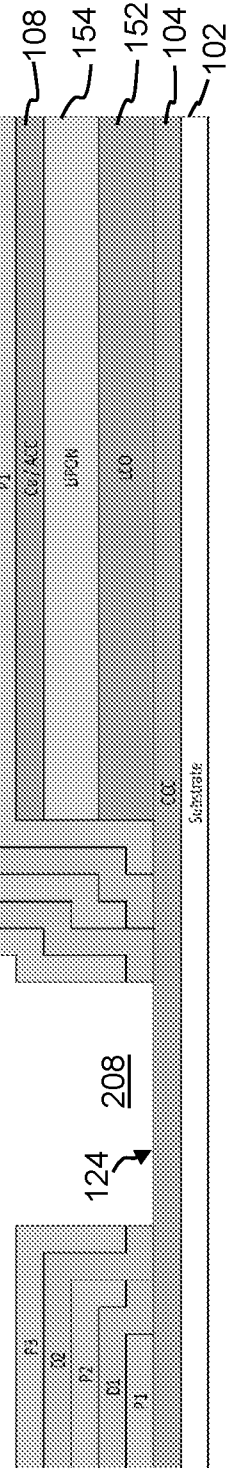
**FIG. 2F**



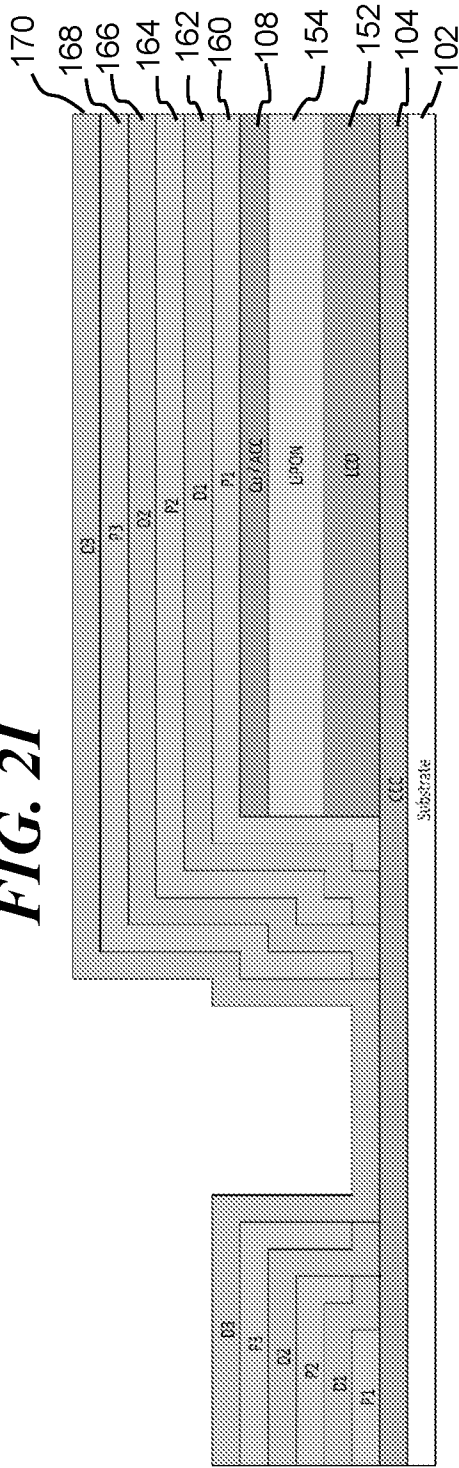
**FIG. 2G**



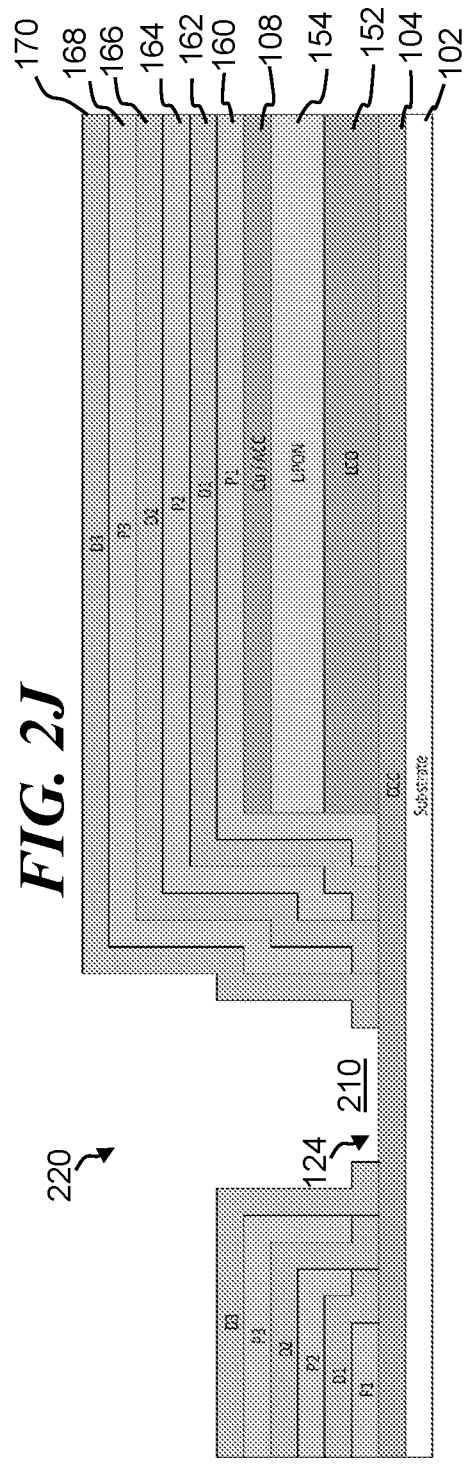
**FIG. 2H**



**FIG. 2I**



**FIG. 2J**





300

**FIG. 3**

**A. CLASSIFICATION OF SUBJECT MATTER****H01M 10/04(2006.01)i, H01M 10/0585(2010.01)i, H01M 2/02(2006.01)i, H01M 2/10(2006.01)i, H01M 10/0562(2010.01)i, H01M 4/139(2010.01)i, H01M 4/04(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

H01M 10/04; C23C 14/00; C23F 1/00; C23C 14/34; H01M 6/00; H01M 6/40; H01M 4/04; H01M 10/0585; H01M 2/02; H01M 2/10; H01M 10/0562; H01M 4/139

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models  
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) &amp; keywords: thin film battery, cathode current collector, anode current collector, thin film encapsulant, extending

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008-0032236 A1 (WALLACE, MARK A. et al.) 07 February 2008 See claims 1, 18; paragraph [0094]; figure 18.	1-15
A	WO 2016-037109 A1 (APPLIED MATERIALS, INC.) 10 March 2016 See claim 1; figure 34.	1-15
A	US 2015-0325862 A1 (APPLIED MATERIALS, INC.) 12 November 2015 See claim 1; figure 4D.	1-15
A	US 2008-0213664 A1 (KRASNOV, VICTOR et al.) 04 September 2008 See claim 1.	1-15
A	US 2014-0007418 A1 (SONG, DAOYING et al.) 09 January 2014 See claim 1.	1-15

 Further documents are listed in the continuation of Box C. See patent family annex.

\* Special categories of cited documents:

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

19 July 2017 (19.07.2017)

Date of mailing of the international search report

**20 July 2017 (20.07.2017)**

Name and mailing address of the ISA/KR

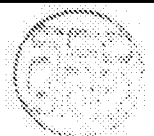
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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2017/027580**

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