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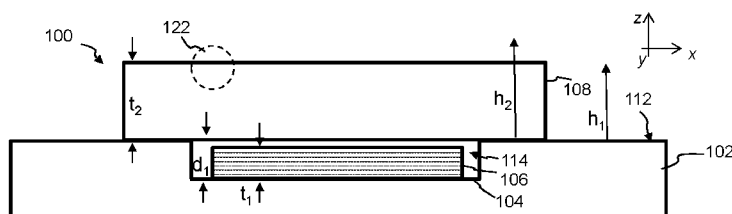


FIG. 1A

- (57) Abstract: A device. The device may include: a substrate, the substrate comprising: an upper surface; and a recess extending from the upper surface into the substrate; an active device region, the active device region disposed within the recess and having a first thickness; and an encapsulant, the encapsulant disposed over the recess and over the active device region, wherein the encapsulant has a second thickness, wherein the encapsulant extends above the upper surface of the substrate to a first distance, and wherein the first distance is less than a sum of the first thickness and second thickness.



THIN FILM BATTERY DEVICE HAVING RECESSED SUBSTRATE 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] Thin film batteries may enable an increasing number of applications because of their compact size. As an example, a medical battery cell is a thin film-based micro battery device built from a battery cell stack deposited on a substrate, where the thickness of the active battery components may be on the order of 45 micrometers. Additionally, an encapsulation having a thickness on the order of 40 micrometers to 100 micrometers, such as 45 micrometers, may be deposited over the active battery components. The different active battery components and encapsulant may be deposited as a series of thin layers (thin films) and patterned to form a targeted device structure. Providing adequate step-coverage of such a structure presents challenges, such as avoiding step-coverage-related layer breakage. Step-coverage breakage of a metallization layer carrying active electrical current may result in catastrophic failure of functionality in such a device. Step-coverage breakage of a dielectric or a metal layer functioning as a gas and moisture permeation barrier may result in gas and moisture permeation from the cell ambient to the cell interior, leading to poor cell cycle life. Furthermore, the cell structure step-ledges are very

vulnerable to degradation induced by cell volume expansion of the thin film battery structure during cell cycling operations of a thin film battery.

[0004] With respect to these and other considerations the present disclosure is provided.

Brief Summary

[0005] In one embodiment, a device may include a substrate, the substrate comprising: an upper surface; and a recess extending from the upper surface into the substrate; an active device region, the active device region disposed within the recess and having a first thickness. The device may include an encapsulant, the encapsulant disposed over the recess and over the active device region, wherein the encapsulant has a second thickness. The encapsulant may extend above the upper surface of the substrate to a first distance, and wherein the first distance is less than a sum of the first thickness and second thickness.

[0006] In another embodiment, a thin film battery may include a substrate, the substrate comprising: an upper surface; and a recess extending from the upper surface into the substrate along a first direction. The battery may include an active device region, the active device region being disposed within the recess and having a first thickness. The active device region may include a lithium-containing cathode; a solid state electrolyte disposed on the lithium-containing cathode; and an anode region disposed on the solid state electrode; and an encapsulant disposed on the active device region. The encapsulant may include at least one rigid layer and at least one polymer layer.

[0007] In another embodiment, a method of forming a device, may include: providing a substrate having an upper surface; forming a recess within the substrate, the recess extending from the upper surface into the substrate; forming an active device region within the recess, the active device region having a first thickness; and forming an encapsulant over the active device region,

wherein the encapsulant has a second thickness, and wherein the encapsulant extends above the upper surface of the substrate to a first distance, wherein the first distance is less than a sum of the first thickness and second thickness.

Brief Description of the Drawings

- [0008] **FIG. 1A** shows a device arranged according to embodiments of the disclosure;
- [0009] **FIG. 1B** shows a device arranged according to other embodiments of the disclosure;
- [0010] **FIG. 2A** shows another device according to further embodiments of the disclosure;
- [0011] **FIG. 2B** shows an exemplary active device region according to various embodiments of the disclosure;
- [0012] **FIG. 2C** shows another device according to further embodiments of the disclosure;
- [0013] **FIG. 3** illustrates a particular embodiment of a thin film battery;
- [0014] **FIG. 4** presents an exemplary process flow according to embodiments of the disclosure;
- [0015] **FIG. 5** presents another exemplary process flow according to other embodiments of the disclosure; and
- [0016] **FIG. 6** presents a further exemplary process flow according to embodiments of the disclosure.
- [0017] The drawings are not necessarily to scale. The drawings are merely representations, not intended to portray specific parameters of the disclosure. The drawings are intended to depict exemplary embodiments of the disclosure, and therefore are not be considered as limiting in scope. In the drawings, like numbering represents like elements.

[0018] Furthermore, certain elements in some of the figures may be omitted, or illustrated not-to-scale, for illustrative clarity. The cross-sectional views may be in the form of "slices", or "near-sighted" cross-sectional views, omitting certain background lines otherwise visible in a "true" cross-sectional view, for illustrative clarity. Furthermore, for clarity, some reference numbers may be omitted in certain drawings.

Detailed Description

[0019] 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.

[0020] The present embodiments are related to device structures, such as thin film battery structures and fabrication methods, where exemplary device structures provide an improved topography as compared to known device structures. To this end, various embodiments provide a recessed cell stack structure for a thin film battery, where at least a portion of a cell stack forming the thin film battery components is recessed into the host substrate. In this manner, a battery cell's surrounding edges may be protected by the walls of a recess provided in the substrate.

[0021] **FIG. 1A** depicts a device 100 according to various embodiments of the disclosure. The device 100 may represent a thin film device, such as a thin film battery in some embodiments. In other embodiments, the device 100 may represent a non-thin film device, such as a larger battery. As shown in FIG. 1A, the device 100 includes a substrate 102 having an upper surface 112. The substrate 102 may also include a recess 104 extending from the upper surface 112.

into the substrate 102 for a distance d_1 . Additionally, the device may include an active device region 106, where the active device region 106 is disposed within the recess 104. The active device region 106 may include a plurality of components forming part of an active device, such as a plurality of structures forming the active part of a battery.

[0022] In embodiments where device 100 represents a thin film battery, the active device region 106 may comprise a cell stack formed from a plurality of layers, where the different layers function as different parts of the battery. Examples of such layers include a cathode current collector, a lithium-containing cathode, a solid state electrolyte, where the solid state electrolyte may be disposed on the lithium-containing cathode, an anode region disposed on the solid state electrolyte, an anode (*e.g.*, Li metal) and a current collector, and so forth. While such layers may be initially deposited in blanket form, the layers may be subsequently patterned to form the active device region 106 as a cell stack, where the active device region 106 is located within the recess 104 as shown.

[0023] The active device region 106 as shown may have a first thickness represented by t_1 . In various embodiments, the relative size of d_1 and t_1 may be arranged to accommodate the active device region 106 partially or completely within the recess 104. As shown in the example of FIG. 1A, d_1 may be greater than t_1 , resulting in the active device region 106 being completely contained within the recess 104, meaning the top of active device region 106 is below the upper surface 112. As an example, in the case of a thin film battery t_1 may be 45 μm , while d_1 is 50 μm . The embodiments are not limited in this context.

[0024] As further shown in FIG. 1A, the device 100 may include an encapsulant 108, where the encapsulant 108 is disposed on or over the active device region 106, and where the encapsulant 108 may also be disposed over the upper surface 112 as shown. In some embodiments,

the encapsulant 108 may be formed using known encapsulant materials for encapsulating thin film batteries. The encapsulant 108 may have a second thickness shown as t_2 in FIG. 1A. As an example, in the case of a thin film battery, the encapsulant 108 may have a thickness in the range of 40 μm to 100 μm and in particular embodiments a thickness of 45 μm . The embodiments are not limited in this context.

[0025] In the example geometry of FIG. 1A, the encapsulant 108 may have a planar structure wherein the encapsulant 108 extends above the upper surface 112 to a first distance, represented by h_1 . Because of the planar structure of encapsulant 108, the first distance may be equivalent to the thickness, t_2 , of the encapsulant 108. An advantage provided by the structure of device 100 is the lesser topography generated by the combination of the active device region 106 and encapsulant 108, as compared to known thin film batteries. In particular, because in the present embodiment the active device region 106 is formed on the bottom of the recess 104, and not on the upper surface 112, the active device region 106 and encapsulant 108 together generate a profile extending just to h_1 , above the upper surface 112. Additionally, there is no offset or curvature in the profile of the encapsulant 108 in the region 122, as compared to the profile 120.

[0026] In other embodiments, convenience or other considerations may dictate the depth of a recess being less than t_1 . Turning now to **FIG. 1B** there is shown another embodiment of a device, device 150 where the device 150 is similar to device 100. In this case the device 150 includes a recess 154 where the depth of the recess 154 is represented by d_2 . In this case, d_2 is less than t_1 , generating an encapsulant 108 having a profile 120, extending to a height h_2 above the upper surface 112 in the region above the recess 154, as shown in FIG. 1B. Depending upon the extent of height h_2 of the resulting encapsulant 108 after deposition, this structure may also provide an advantage over known thin film devices, where an active device region 106 may be formed on

the upper surface 112, resulting in the encapsulant projecting to a greater extent above the upper surface 112.

[0027] In either circumstance of FIG. 1A or FIG. 1B, the device 100 or device 150 may be arranged wherein the encapsulant 108 extends above the upper surface of the substrate to a first distance (h_1), wherein h_1 is less than a sum of the first thickness (t_1) of the active device region 106 and second thickness (t_2) of the encapsulant. The advantages afforded by these configurations may be further illustrated using "realistic" values for the various entities of a thin film battery as embodied by device 100. As an example where the thickness of the active device region of a thin film battery, t_1 , is 45 μm , d_1 is 50 μm , and the encapsulant thickness, t_2 , is 45 μm , the structure of FIG. 1A may yield a value of h_1 of 45 μm . This value for h_1 of 45 μm means the thickness of the active device region 106 does not contribute to the value of h_1 since the thickness of the encapsulant t_2 , is just 45 μm . Accordingly, a device stack including the active device region 106 and encapsulant 108, having a total thickness of 90 μm , is accommodated in the device 100 in a manner where the device stack extends just 45 μm above the upper surface 112 of substrate 102. Notably, a similar device stack having a total thickness of 90 μm and constructed where the active device region is formed on the upper surface 112, would extend 90 μm above the upper surface 112 (*see* h_2). Accordingly, in this example, the topography generated by a thin film battery above the upper surface of a substrate is reduced by 50% in comparison to a known device structure. This structure provides a further advantage of reducing the Z-axis height variation so as to accommodate better Z-axis lithographic pattern lens focusing capability for patterning to be performed using optical lithography, as an example.

[0028] As further illustrated in FIG. 1A, the recess 104 may be larger than the active device region 106, including within the X-Y plane of the Cartesian coordinate system shown. In various

embodiments as discussed further below, material may be provided within a region 114 to encompass the active device region 106 within the recess 104, including the gap between the top of active device region 106 and the bottom of encapsulant 108. In some embodiments, this material may be provided in addition to the encapsulant 108.

[0029] Turning now to **FIG. 2A**, there is shown a device 200 according to further embodiments of the disclosure. In this embodiment, the device 200 may represent a thin film battery, where the active device region 106 includes a plurality of layers. **FIG. 2B** depicts a variant of the active device region including a cathode current collector 212, a lithium-containing cathode 214, a solid state electrolyte 216, an anode region 218 and an anode current collector 220. Again, the active device region 106 is disposed in a recess 104 as detailed above with respect to FIG. 1. The substrate 102 may be formed of a material such as yttria stabilized zirconium oxide (YSZ), alumina, a ceramic, or other known material for forming a thin film battery. The embodiments are not limited in this context.

[0030] The device 200 may also include an encapsulant 202, where the encapsulant 202 includes a plurality of layers. The encapsulant 202 may be a thin film encapsulant where a total thickness (along the Z-axis) of the encapsulant 202 is on the order of tens of micrometers, such as 10 μm to 100 μm . The embodiments are not limited in this context. As an example, the encapsulant may include a layer 204 composed of a first material and a layer 206 composed of a second material. The first material and second material may perform different functions in some embodiments. For example, layer 204 may be a polymer layer, and in some embodiments may be a soft and pliable polymer, providing flexibility to the encapsulant 202. In various embodiments, when the layer 204 is a polymer layer, this layer may be composed of multiple polymer sub-layers, where the properties of the different polymer sub-layers may vary among one another. For

example, one polymer sub-layer of the polymer layer may be especially flexible as compared to other polymer sub-layers.

[0031] Layer 206 may be a rigid layer, such as rigid dielectric, rigid metal, such as Cu, Al, Pt, Au, or other metal, or rigid polymer, used as a permeation blocking layer to prevent diffusion of species through the encapsulant, such as contaminant species present in ambient surrounding the device 200. The layer 204 and layer 206 may be arranged in repeating fashion as shown. In particular embodiments, the layer 204 may be a polymer layer and layer 206 may be a rigid dielectric layer, such as silicon nitride. According to different embodiments, the sequence of layer 204 and layer 206 may repeat two or more times. The embodiments are not limited in this context. In various embodiments, in the encapsulant 202, the layers 204, which layers may be a polymer layer, may be encapsulated within the encapsulant 202, such as shown schematically in FIG. 2A. As such, the layer 206, as well as subsequent layers, may encapsulate a given polymer layer to create a permeation blocking layer, including around edges of a polymer layer.

[0032] 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 or rigid dielectric 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.

[0033] As further shown in FIG. 2A, the device 200 may include a first electrical contact 208 and a second electrical contact 210, where these contacts are used to connect to a cathode and anode, respectively, of a thin film battery. As in the embodiment of FIG. 1A, because

the active device region 106 is disposed within the recess 104, the active device region 106 and encapsulant 202 present a reduced topography as compared to known thin film battery structures.

[0034] Additionally, because the various layers of the encapsulant 202 are not disposed on an active device structure extending above the upper surface 112, the various layers, including layer 204 and layer 206, may be formed on a flat surface and may extend in a planar fashion as shown in the X-Y plane, while not bending. For example, referring also again to FIG. 1B, there are shown partial contours of a layer 124 and a layer 126 generated under the scenario of profile 120, assuming the encapsulant 108 is formed from multiple layers. In the example of FIG. 1B, the layer 124 and layer 126 may bend in the region 122. In the extreme case of known thin film devices where the encapsulant is formed on top of an active device stack extending from the upper surface 112, the profile of an encapsulant may be even sharper in the region 122, resulting in severe bending and strain or stress on the layers formed in such an encapsulant. Notably, in FIG. 2A the layers of encapsulant 202 do not bend since the top of encapsulant 202 is planar. Accordingly, this planar structure places less stress on the individual layers of the encapsulant 202, making failure less likely and providing longer life to a battery cell.

[0035] **FIG. 2C** depicts a thin film battery 250 according to further embodiments of the disclosure. In this example, the active device region may include a cathode current collector 222, cathode 224, solid state electrolyte 226, anode 228, and anode current collector 230. After formation of the recess 104, the cathode current collector 222, cathode 224, solid state electrolyte 226, anode 228, and anode current collector 230 may be formed by blanket deposition and patterning. In this embodiment, the cathode current collector 222 and anode current collector 230 extend to opposite sides of encapsulant 202, in a coplanar configuration with one another. This arrangement may provide a structure more resistant to attack from ambient species

as compared to device 200. In various embodiments, fill material may be provided in the region 232.

[0036] Turning now to **FIG. 3** there is shown a structure of a thin film battery 300 according to further embodiments of the disclosure. The thin film battery 300 may include some of the components of the device 200, where like components are labeled the same. A hallmark of the thin film battery 300 is the provision of a planarizing polymer layer 302, disposed between the encapsulant 202 and the active device region 106. In some embodiments the planarizing polymer layer 302 may be composed of a cured polymer. Examples of a cured polymer include a silicone, an epoxy, or a polyimide. In some embodiments, the planarizing polymer layer 302 may be dispensed as a liquid or relatively lower viscosity material into the recess 104 after formation of the active device region 106 in the recess 104. The planarizing polymer layer 302 may be subsequently cured to form a solid layer. The planarizing polymer layer 302 may further extend over the upper surface 112. After formation, the planarizing polymer layer 302 may present a planar surface for depositing of the encapsulant 202. As shown, the planarizing polymer layer 302 may be encapsulated by a layer 206, such as a rigid metal layer or rigid dielectric layer, acting as a permeation blocking layer. The thickness of the planarizing polymer layer 302 above the upper surface 112 may range from 5 μm to 60 μm in some embodiments. While not specifically shown, a planarizing polymer layer may optionally be included in the embodiment of FIG. 1, for example. In a variant of the thin film battery 300, cathode current collector and anode current collector contacts may be formed to the sides of encapsulant 202, so as to extend over the upper surface 112, as shown in FIG. 2C, for example.

[0037] According to various embodiments, the planarizing polymer layer 302 (as well as the layer 204) may be a soft and pliable material, and may have either a high elongation to break

or a low elastic modulus, or the two properties. Examples of useful polymer properties for planarizing polymer layer 302 include a high elongation to break, defined herein as an elongation to break of 70% or greater. Other exemplary properties of a planarizing polymer layer 302 include a relatively lower modulus than a rigid layer, where a low elastic (Young's) modulus as used herein is an elastic modulus less than 20 GPa (*e.g.*, 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). A rigid dielectric layer may be composed of a known material such as silicon nitride (silicon nitride: Vicker's hardness of ~ 13 GPa, Young's Modulus of ~ 43500 Kpsi or ~ 300 GPa), where the hardness and elastic modulus are greater than the polymer layer.

[0038] In this manner, the planarizing polymer layer 302 may provide a cushion to absorb the effect of changes in volume in the active device region 106 during operation of the thin film battery 300. For example, during charging and discharging of a lithium-based thin film battery, the anode region (as well as cathode) may undergo a reversible expansion and contraction as lithium diffuses into and out of the anode region (cathode). This reversible dilation may represent a change in dimension on the order of 5 μm or more along the Z-axis for active device regions having dimensions on the order of 50 μm along the Z-axis. The provision of the planarizing polymer layer 302 may accommodate this dilation in the active device region 106 by allowing elastic deformation of the planarizing polymer layer to compensate for the dilation. In this manner, less stress or strain may be imparted to other regions of the thin film battery 300, such as in rigid dielectric layers of the encapsulant 202. In turn, this lower stress or strain may result in less cracking or delamination of the encapsulant or of layers within the active device region 106,

especially at the perimeter of an active region of the thin film battery 300. The reliability of interconnect structures such as first electrical contact 208 and second electrical contact 210 may also be improved for the same reasons. Accordingly, in addition to providing a lesser topography above the upper surface 112, the thin film battery of 300 may provide improved protection against gas and moisture permeation, and thus better device performance as well as improved device lifetime

[0039] Turning now to **FIG. 4** there is shown a process flow 400 according to some embodiments of the disclosure. At block 402, a substrate is provided having an upper surface. The substrate may be a planar substrate such as a polycrystalline ceramic, oxide, monocrystalline material, semiconductor, or polymer in different embodiments.

[0040] At block 404, a recess is formed in the substrate, where the recess extends from the upper surface of the substrate into the substrate. The recess may be formed to a target depth designed to accommodate device structures to be formed. In various embodiments, the recess, including in the active device area, may exhibit a localized height variation (along the Z-axis), where this height variation may increase the effective battery cell area, resulting in increased cell capacity.

[0041] At block 406, an active device region having a first thickness is formed in the active area recess. In particular embodiments, the active device region may include a plurality of layers, such as a cell stack composed of layers for forming a thin film battery. The first thickness of the active device region may be chosen so as to place the active device region entirely within the recess, or partially within the recess in different embodiments. In some examples, the active device region may be formed by depositing a plurality of layers in blanket form on the substrate so as to form a stack of layers. The stack of layers may be subsequently patterned and etched so as to

remove material of the stack of layers not located in the recess. In some embodiments, the r stack of layers may be formed and patterned in a manner where a cathode current collector and anode current collector extend out of the active area recess, and onto the upper surface of the substrate.

[0042] In one particular example, forming the active device region may involve operations including depositing a cathode current collector; depositing a lithium-containing cathode layer on the cathode current collector; depositing a solid state electrolyte layer on the lithium-containing cathode layer; depositing an anode layer of the solid state electrolyte layer; depositing an anode current collector; wherein the cathode current collector, the lithium-containing cathode layer, solid state electrolyte, the anode layer, and the anode current collector form an active device stack; and patterning the active device stack to define a patterned stack disposed within the recess.

[0043] At block 408, a planarization layer is formed over the active device region and the recess. The planarization layer may be a planarizing polymer layer in some embodiments. In some embodiments, the planarization layer may be formed by dispensing a relatively low viscosity, liquid like material, onto the substrate, where the low viscosity material fills the recess around the active device region. The planarization layer may further extend over the upper surface of the substrate in some embodiments. When dispensed as a liquid, the planarization layer may be subsequently cured to form a solid, such as in the case of silicones, epoxies, and other curable polymers.

[0044] At block 410, an encapsulant is formed over the planarization layer and the active device region. The encapsulant may extend over at least a portion of the upper surface of the substrate in various embodiments. In some embodiments, the encapsulant may include a plurality of layers, where different layers are formed from different materials. In some embodiments, the encapsulant may include a rigid layer, such as a rigid metal or rigid dielectric, where the rigid layer

encapsulates the planarization layer at the upper surface of the substrate. The encapsulant may be formed, for example, by depositing a plurality of different layers in blanket form to generate a thin film encapsulant arranged as a stack of layers having a target thickness for the encapsulant. In some embodiments, the thin film encapsulant may be subsequently patterned to define an encapsulant structure extending over the recess and the active device region, and extending partially over the upper surface of substrate. The encapsulant and portions of the underlying active device region may be further patterned to provide for contact structures to the active device region. In some embodiments, where the anode current collector and cathode current collector extend along the upper surface of the substrate, patterning may be performed so as to exposed the anode current collector and cathode current collector for external contacts (as in FIG. 2C).

[0045] Turning now to **FIG. 5** there is shown another process flow 500 according to embodiments of the disclosure. At block 502, a substrate precursor is provided in a green state. A green state may refer to a state of a substrate where the substrate microstructure is not in final form, and may include material to be subsequently removed or transformed by application of heat. An example of a ceramic substrate precursor in a green state may be a composite including ceramic powder mixed with a combination of other material such as a liquid and a polymer. In the green state the ceramic substrate precursor may have semi-solid properties, rendering the substrate amendable to shaping and molding.

[0046] At block 504, the operation of molding the substrate precursor in the green state is performed using a mold, where the mold may have a designed shape and size to form a recessed structure having an initial size within the ceramic precursor. In various embodiments, the mold may be a mold stamp, a textured mold roller, a Gravure roller with laser defined relief patterns or a printing blanket with defined relief patterns, and so forth. The recessed structure may have, for

example, a dimension in one or more directions larger than the target size for a final recess, such as approximately 20% larger in one example.

[0047] At block 506, the substrate precursor, including the recessed structure, is heated to form a final substrate, wherein a recess is formed in the final substrate, wherein the recess has a final size different than the initial size of the recessed structure formed in the substrate precursor.

[0048] Turning now to **FIG. 6** there is shown another process flow 600 according to other embodiments of the disclosure. At block 602, a planar substrate is provided where the planar substrate has an upper surface. At block 604, the substrate is etched to form a recess. The substrate may be etched using laser micromachining or lithographic patterning and etching to a target depth and according to a target size and shape. The size and shape of the recess as well as the depth of the recess may be arranged to accommodate an active device region of an active device to be formed in the recess. In various embodiments, the recess, including in the active device area may exhibit localized height variation (along the Z-axis), where this height variation may increase the effective battery cell area, resulting in increased cell capacity.

[0049] While the aforementioned embodiments focus on applications for thin film batteries, in other embodiments, a battery structure designed for larger batteries may be formed using a substrate recess according to the principles of the aforementioned embodiments.

[0050] There are multiple advantages provided by the present embodiments, including the ability to reduce the distance a device stack extends above a substrate upper surface, including the active device region and encapsulant, while not having to reduce the thickness of either the active device region or encapsulant. Further advantages include the ability to reduce stress, cracking, and delamination in a thin film device while not changing properties or dimensions of individual components of the thin film device. Another advantage is the overall reduction of device height

above a substrate, afforded by forming a portion of the thin film device within a recess in a substrate.

[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 device, comprising:
 - a substrate, the substrate comprising:
 - an upper surface; and
 - a recess extending from the upper surface into the substrate;
 - an active device region, the active device region disposed within the recess and having a first thickness; and
 - an encapsulant, the encapsulant disposed over the recess and over the active device region, wherein the encapsulant has a second thickness, wherein the encapsulant extends above the upper surface of the substrate to a first distance, and wherein the first distance is less than a sum of the first thickness and second thickness.
2. The device of claim 1, wherein the recess extends to a first depth from the upper surface into the substrate, wherein the first depth is greater than or equal to the first thickness.
3. The device of claim 1, the active device region comprising a plurality of layers.
4. The device of claim 3, wherein the device is a thin film battery, the plurality of layers comprising:
 - a cathode current collector;
 - a lithium-containing cathode;
 - a solid state electrolyte disposed on the lithium-containing cathode; and
 - an anode region disposed on the solid state electrolyte;

and an anode current collector disposed on the anode region, the anode current collector being further disposed adjacent the encapsulant.

5. The device of claim 1, wherein the encapsulant comprises a plurality of layers, wherein the plurality of layers comprise at least one rigid layer and at least one polymer layer.

6. The device of claim 1, wherein a portion of the encapsulant is disposed around the active device region within the recess.

7. The device of claim 1, further comprising a planarizing polymer layer disposed between the encapsulant and the active device region.

8. A thin film battery, comprising:

a substrate, the substrate comprising:

an upper surface; and

a recess extending from the upper surface into the substrate along a first direction;

an active device region, the active device region being disposed within the recess and having a first thickness, wherein the active device region comprises:

a lithium-containing cathode;

a solid state electrolyte disposed on the lithium-containing cathode; and

an anode region disposed on the solid state electrolyte; and

an encapsulant disposed on the active device region, wherein the encapsulant comprises:

at least one rigid layer; and

at least one polymer layer.

9. The thin film battery of claim 8, wherein the encapsulant has a second thickness, wherein the encapsulant extends above the upper surface of the substrate to a first distance, and wherein the first distance is less than a sum of the first thickness and second thickness.

10. The thin film battery of claim 8, wherein the recess comprises a localized height variation along the first direction.

11. The thin film battery of claim 8, wherein the active device region further comprises an anode current collector and a cathode current collector, the anode current collector and the cathode current collector extending onto the upper surface of the substrate.

12. The thin film battery of claim 8 wherein the at least one polymer layer is encapsulated within the encapsulant.

13. A method of forming a device, comprising:

providing a substrate having an upper surface;

forming a recess within the substrate, the recess extending from the upper surface into the substrate;

forming an active device region within the recess, the active device region having a first thickness; and

forming an encapsulant over the active device region, wherein the encapsulant has a second

thickness, and wherein the encapsulant extends above the upper surface of the substrate to a first distance, wherein the first distance is less than a sum of the first thickness and second thickness.

14. The method of claim 13, wherein the forming the active device region comprises:
 - depositing a cathode current collector;
 - depositing a lithium-containing cathode layer on the cathode current collector;
 - depositing a solid state electrolyte layer on the lithium-containing cathode layer;
 - depositing an anode layer of the solid state electrolyte layer;
 - depositing an anode current collector; wherein the cathode current collector, the lithium-containing cathode layer, solid state electrolyte, the anode layer, and the anode current collector form an active device stack; and
 - patterning the active device stack to define a patterned stack disposed within the recess.
15. The method of claim 14, wherein the forming the encapsulant comprises:
 - depositing a polymer layer; and
 - depositing a rigid layer, wherein the polymer layer and the rigid layer form a stack of layers.

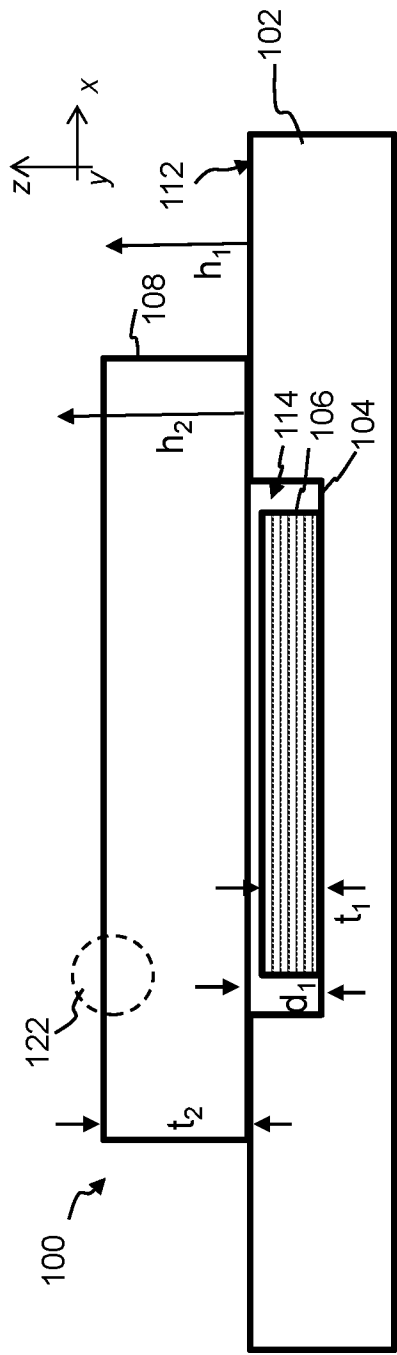


FIG. 1A

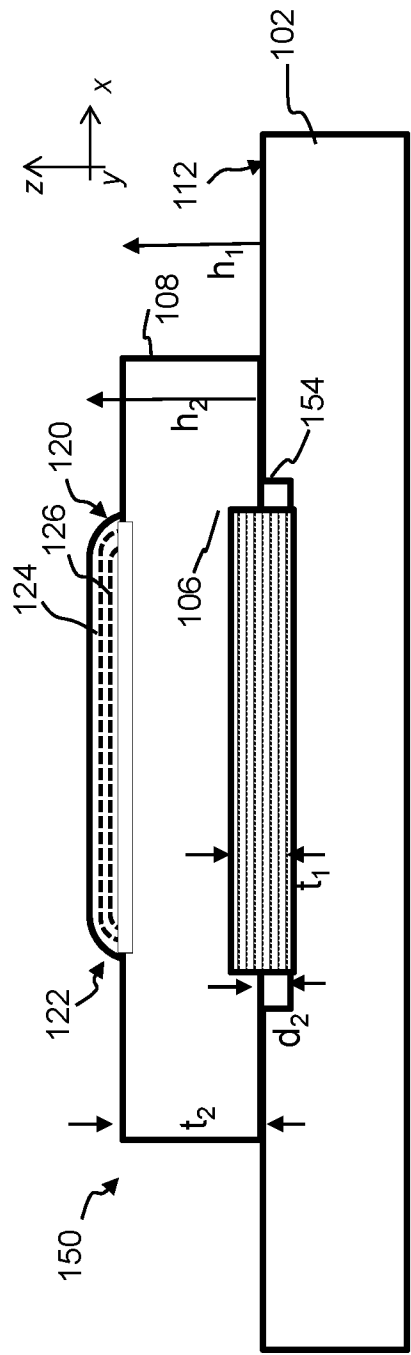
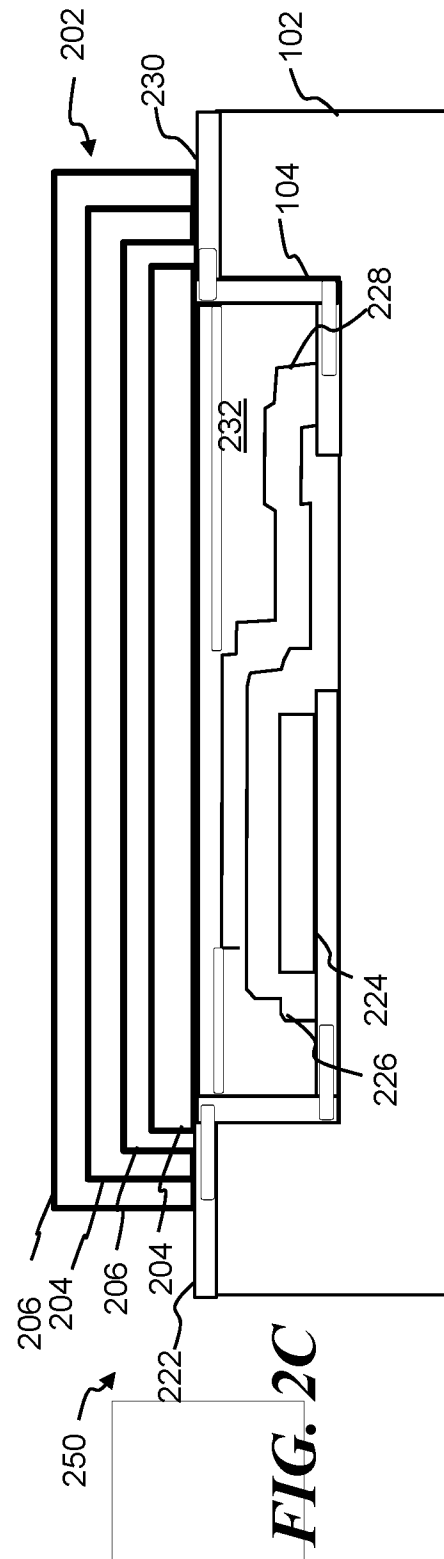
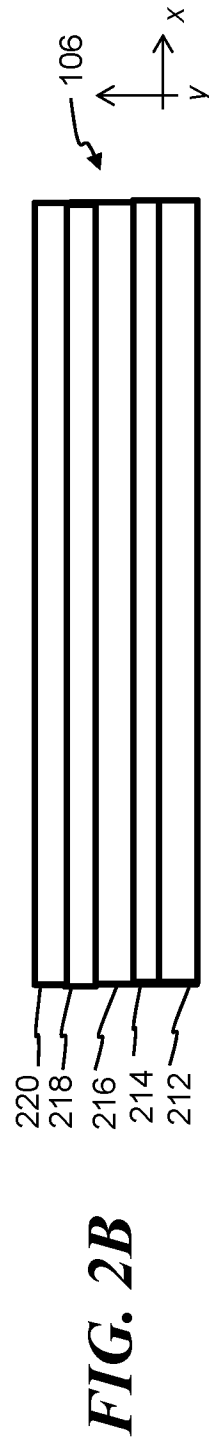
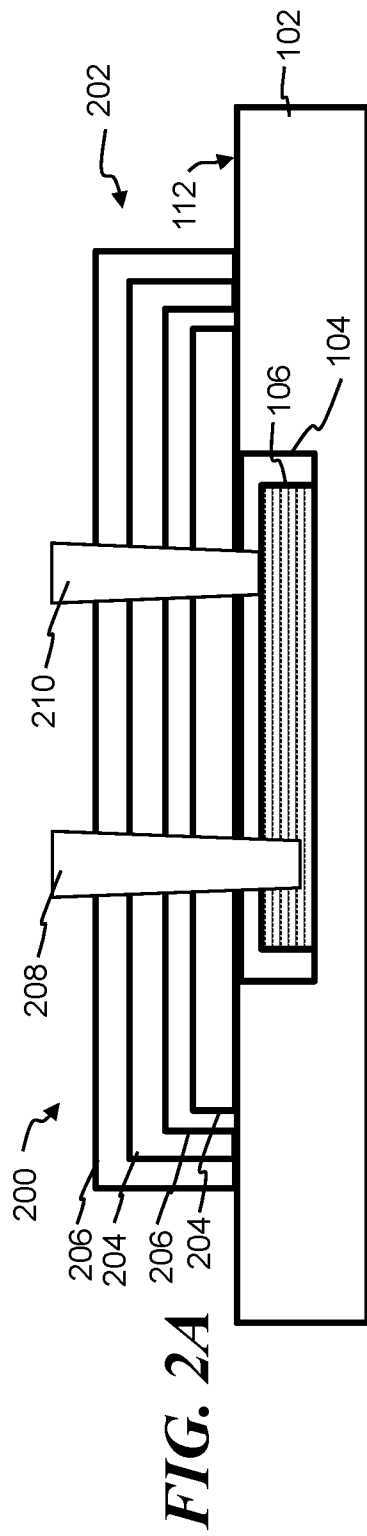
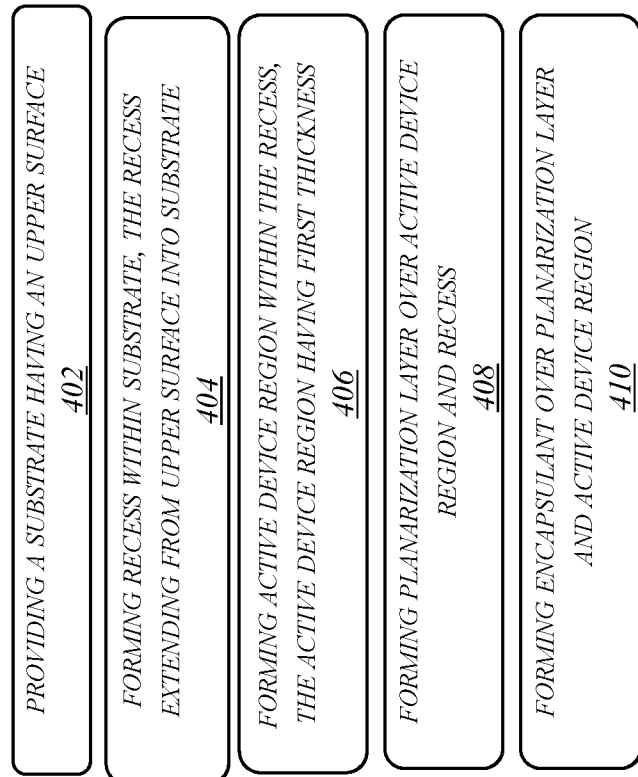
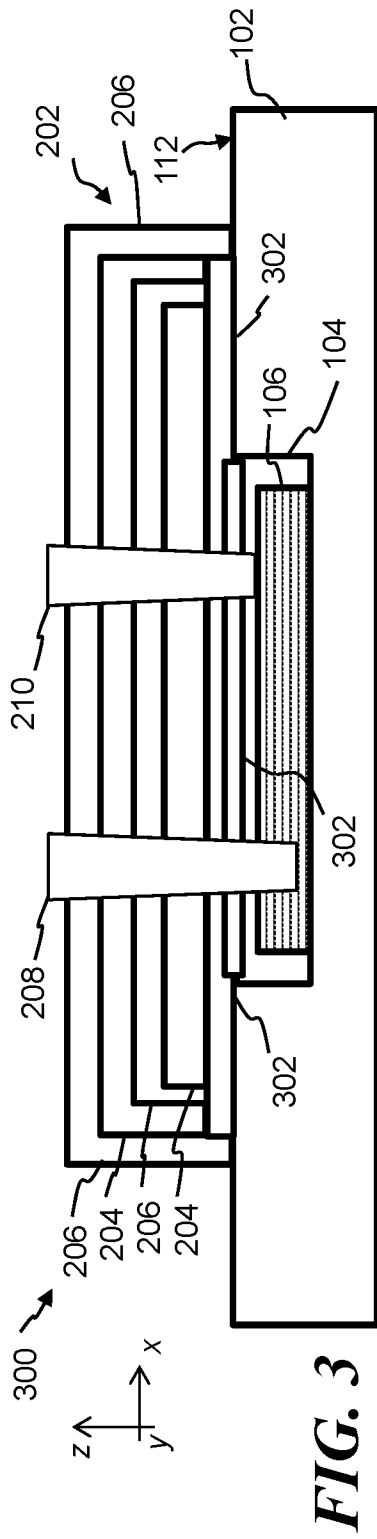


FIG. 1B





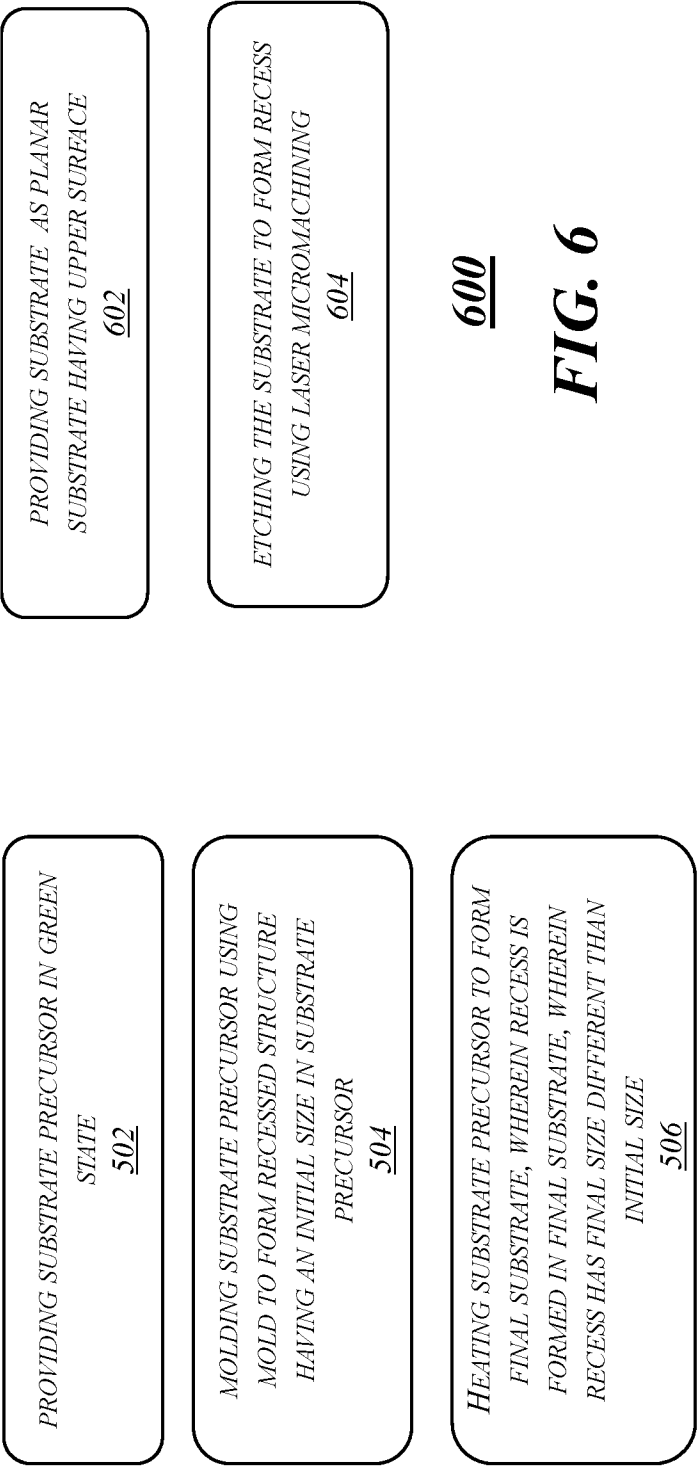


FIG. 5

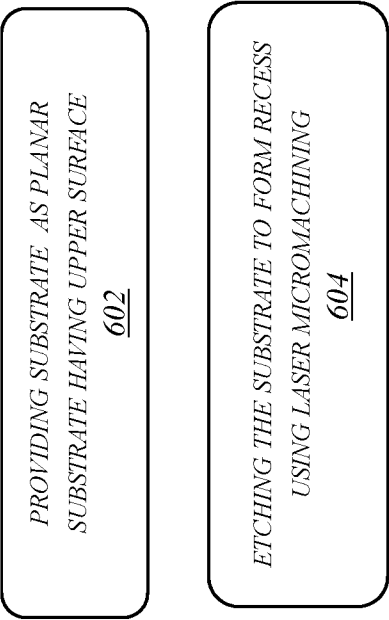


FIG. 6