



- (51) **International Patent Classification:** Not classified
- (21) **International Application Number:**
PCT/US2017/027561
- (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
15/338,958 31 October 2016 (31.10.2016) US
- (71) **Applicant:** APPLIED MATERIALS, INC. [US/US];
3050 Bowers Avenue, Santa Clara, California 95054 (US).
- (72) **Inventors:** KWAK, Byung-Sung; 9723 NW Henry Court,
Portland, Oregon 97229 (US). SUN, Lizhong; 952 Wind-
sor Hills Circle, San Jose, California 95123 (US). PARK,
Giback; 6191 Calle del Conejo, San Jose, California
95120 (US). YOUNG, Michael Yu-Tak; 21210 Rainbow
Drive, Cupertino, California 95014 (US). FRANKLIN,
Jeffrey L.; 1000 Sandia Road NW, Albuquerque, New
Mexico 87107 (US). WANG, Miaojun; 1307 Aspen Lake
Court, San Jose, California 95131 (US).
- (74) **Agent:** DAISAK, Daniel N.; Kacvinsky Daisak Bluni
PLLC, 101 Carnegie Center, Suite 106, Princeton, New
Jersey 08540 (US).

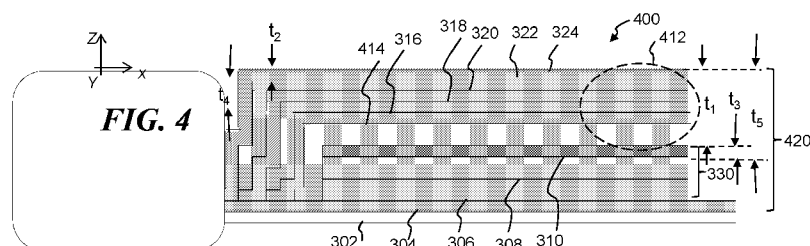
(81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, 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:

— without international search report and to be republished upon receipt of that report (Rule 48.2(g))

(54) **Title:** MULTILAYER THIN FILM DEVICE ENCAPSULATION USING SOFT AND PLIABLE LAYER FIRST



(57) **Abstract:** A thin film device. The thin film device may include: an active device region, the active device region comprising a diffusant; and a thin film encapsulant disposed adjacent to the active device region and encapsulating at least a portion of the active device region, the thin film encapsulant comprising: a first layer, the first layer disposed immediately adjacent the active device region and comprising a soft and pliable material; and a second layer disposed on the first layer, the second layer comprising a rigid dielectric material or rigid metal material.

MULTILAYER THIN FILM DEVICE ENCAPSULATION USING SOFT AND PLIABLE LAYER FIRST

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 electrochemical devices.

Background

[0003] Thin film encapsulation technology is often employed in devices, where the devices are purely electrical devices or electro-optical devices, such as Organic Light Emitting Diodes (OLED). Other than possibly experiencing a small global thermal expansion from heat generation during the device operation, these electrical devices and electro-optical devices do not exhibit volume changes during operation, since just electrons and photons are transported within the devices during operation. Such global effects due to global thermal expansion of a device may affect in a similar fashion every component of a given device including the thin film encapsulant, and thus, may not lead to significant internal stress. In this manner, the functionality of the thin film encapsulant in a purely electrical device or electro-optic device may not be affected by thermal expansion during operation.

[0004] Notably, in an electrochemical device ("chemical" portion), matter such as elements, ions, or other chemical species having a physical volume (the physical volume of electrons may be considered to be approximately zero) are transported within the device during operation with physical volume move. For known electrochemical devices, *e.g.*, thin film batteries (TFB) based upon lithium (Li), Li is transported from one side to the other side of a battery as electrons move around an external circuit connected to the TFB, where the electrons move in an opposite direction to the chemical and elements. One particular example of the volume change experienced by a Li TFB is as follows. When charging a thin film battery having a lithium-containing cathode such as a lithium cobalt oxide (LiCoO₂) cathode (~15μm to 17μm thick LiCoO₂), an amount of Li equivalent to several micrometers thick layer, such as 6 micrometers (given 100% dense material), may be transported to the anode when loading is approximately 1 mAh/cm². When Li returns to the cathode in a discharge process, the same volume reduction may result on the anode (assuming 100% efficiency). The cathode may also undergo a volume change during a charging and discharging cycle, while such changes are smaller as compared to the anode. For example, the volume of a cathode formed from LiCoO₂ material may expand during charging when Li is extracted from the crystalline lattice, while the volume change is relatively small (~ 2%) compared to volume changes occurring at the anode.

[0005] As such, known thin film encapsulant approaches may be lacking in providing the ability to accommodate such volume change in a robust manner, where the thin film encapsulant continues to provide protection of the electrochemical device during repeated cycling of the device.

[0006] With respect to these and other considerations the present disclosure is provided.

Brief Summary

[0007] In one embodiment, a device may include an active device region, the active device region comprising a diffusant; and a thin film encapsulant disposed adjacent to the active device region and encapsulating at least a portion of the active device region. The thin film encapsulant may include: a first layer, the first layer disposed immediately adjacent the active device region and comprising a soft and pliable material; and a second layer disposed on the first layer, the second layer comprising a rigid dielectric material or rigid metal material.

[0008] In another embodiment, a thin film battery may include an active device region, where the active device region comprises: a lithium-containing cathode; and a solid state electrolyte, disposed on the cathode; an anode disposed on the solid state electrolyte. The thin film battery may further include a thin film encapsulant disposed adjacent to the anode and encapsulating at least a portion of the lithium-containing cathode, the solid state electrolyte, and the anode. The thin film encapsulant may include a first layer, the first layer disposed immediately adjacent the active device region and comprising a soft and pliable material; and a second layer disposed on the first layer, the second layer comprising a rigid dielectric material or rigid metal material.

Brief Description of the Drawings

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

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

[0011] **FIG. 2** illustrates a second instance of operation of the thin film device of FIG. 1A, representing a second state of the thin film device;

[0012] FIG. 3 illustrates a thin film battery in accordance with embodiments of the disclosure;

[0013] FIG. 4 shows a thin film battery in accordance with other embodiments of the disclosure in a first device state; and

[0014] FIG. 5 shows another depiction of the thin film battery of FIG. 4 in a second device state.

Detailed Description

[0015] 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.

[0016] The present embodiments are related to thin film encapsulant structures and technology, where the thin film encapsulant is used to minimize ambient exposure of active devices. In the present embodiments, an active device may form an "active device region" within a device including a thin film encapsulant. The present embodiments provide novel structures and materials combinations for thin film encapsulants, where the thin film encapsulants may be used to encapsulate active devices.

[0017] In various embodiments, a device such as a thin film device, is provided with a novel thin film encapsulant encapsulating an active device. Examples of active devices include a piezoelectric device, shape memory alloy device, or microelectromechanical system (MEMS) device in some embodiments. In other embodiments, the film device may be an electrochemical

device. Examples of 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, in various embodiments known electrochemical devices such as thin film batteries may be provided with encapsulation to protect the active component materials.

[0018] The present embodiments also address a problem encountered in devices such as thin film batteries, where a large physical volume change (expansion and contraction) may take place during the operation of the device. More particularly, as noted, volume changes in a device such as a Li thin film battery may take place in a localized or non-uniform manner in a "selective expansion" region, such as an anode region. Various embodiments of the disclosure provide appropriate structures and appropriate thin film encapsulant materials and methods of applying such materials in a device, such as a thin film battery, resulting in device structures meeting stringent thin film encapsulant requirements.

[0019] In various embodiments, a thin film device is provided with a novel combination of thin film encapsulant material and/or structures. The thin film device, such as a thin film battery or electrochromic window, may include a device stack composed of active layers, as well as the thin film encapsulant, which thin film encapsulant may also constitute a multilayer structure.

[0020] According to embodiments of the disclosure, a thin film device may include an active device region and a thin film encapsulant. The active device region may include a source region comprising the diffusant; and a selective expansion region, wherein transport of the diffusant takes place reversibly between the source region and the selective expansion region.

[0021] In embodiments where the thin film device is a Li thin film battery, a cathode may act as the source region and may include a cathode such as LiCoO_2 or similar material. In the case of electrochromic windows, the concomitant change in volume of a given electrode region may be smaller than in thin film batteries. In embodiments of a Li thin film battery, an anode may act as a selective expansion region, where a large volume change takes place selectively in the selective expansion region, as opposed to other regions in the thin film device.

[0022] In embodiments of a Li thin film battery, an anode may act as a selective expansion region, where a large volume change takes place selectively in the selective expansion region, as opposed to other regions in the thin film device.

[0023] To accommodate changes in volume in a selective expansion region, various embodiments provide materials and/or structures in a thin film encapsulant, where the thin film encapsulant is effective to accommodate volume expansion, as well as contraction in the selective expansion region, rendering a more robust thin film device.

[0024] In various embodiments of the disclosure, a novel thin film encapsulant is arranged adjacent a selective expansion region of a thin film device, such as an anode, where the thin film encapsulant includes a stack of layers. In particular embodiments, the thin film encapsulant includes a first layer, where the first layer is disposed immediately adjacent the selective expansion region and is formed from a soft and pliable material capable of accommodating a change in physical volume in the selective expansion region. The thin film encapsulant may further include a second layer adjacent the first layer, where the second layer is a rigid metal layer or rigid dielectric layer, and where the rigid dielectric layer or rigid metal layer is less pliable than the first layer. An advantage of a rigid metal layer is the rigid metal layer may provide strength while being less brittle than a rigid dielectric layer.

[0025] According to various embodiments, the thin film encapsulant of a thin film encapsulant may encapsulate at least portions of the source region and the selective expansion region. In various embodiments, the thin film encapsulant, at least in a portion adjacent the selective expansion region, may reversibly vary thickness from a first thickness to a second thickness in order to accommodate changes in volume or thickness of materials in the selective expansion region. For example, in a thin film battery where an anode or a portion of an anode may constitute a selective expansion region, the anode may change in thickness by several micrometers as a result of lithium migration, between a charged state and a discharged state in the thin film battery. In the present embodiments, the thin film encapsulant may expand or contract in thickness to accommodate the increase or decrease in anode thickness, resulting in less stress, less mechanical failure, and better protection of the active device of a thin film device.

[0026] In particular embodiments, and as detailed below, a largest fraction of the reversible contraction and expansion of the thin film encapsulant may take place in a first layer of the thin film encapsulant. In particular, the first layer may be a soft and pliable layer, and second layer of the thin film encapsulant may be a permeation blocking layer. The second layer may be a rigid metal layer or rigid dielectric layer, acting as a diffusion barrier such as a moisture barrier or gas barrier, or a barrier to diffusion of other species.

[0027] Turning now to **FIG. 1A** there is shown a thin film device 100 according to embodiments of the disclosure. The thin film device 100 may constitute an electrochemical device such as a thin film battery, electrochromic window, or other electrochemical device. In the embodiment of FIG. 1A, the thin film device 100 may include a substrate base, referred to as the substrate 102, and a source region 104 disposed on the substrate 102. In various

embodiments, the source region 104 may represent a cathode of a thin film device such as a thin film battery or an electrochromic window. The source region 104 may act as a source of a diffusant such as lithium, where the diffusant may reversibly diffuse between the source region 104 and to the selective expansion region 108. The thin film device 100 may also include an intermediate region 106 disposed on the source region and a selective expansion region 108 disposed on the intermediate region 106. The selective expansion region 108 may be an anode, for example, of a thin film device. In the instance shown in FIG. 1A, the thin film device 100 may represent a thin film battery in a first device state, such as a discharged state, where the battery is not charged, meaning a diffusant 114, such as lithium, is depleted from the anode.

[0028] The thin film device 100 further includes a thin film encapsulant 110, where the thin film encapsulant 110 may include a plurality of layers as suggested in FIG. 1A. The thin film encapsulant 110 is disposed immediately adjacent the selective expansion region 108. In this example, the selective expansion region 108 remains relatively contracted, while the thin film encapsulant 110 is relatively expanded or relaxed, as represented by the first thickness t_1 . As shown in FIG. 1B, the thin film encapsulant 110 may include a first layer 122, where the first layer 122 is disposed immediately adjacent the selective expansion region 108, and where the first layer 122 comprises a soft and pliable material. In various embodiments, the first layer 122 may be a polymer layer, where the polymer layer is a soft and pliable layer, enabling the polymer layer to reversibly expand and contract. In various embodiments, the term "polymer layer" as referred to herein, may constitute a polymer layer stack where the polymer layer stack includes at least one polymer layer, and may include multiple layers, which layers may be referred to as sub-layers. Accordingly, the first layer 122 may constitute a polymer layer stack

including multiple sub-layers of different polymers, where at least one sub-layer is soft and pliable.

[0029] In various embodiments, the first layer 122 may be a getter/absorbent infused polymer, a porous low dielectric constant material, a silver paste, an epoxy, a printed circuit board material, or a photo-resist material, and a combination thereof. In addition to the aforementioned materials, particular examples of suitable polymer materials include silicone, rubber, urethane, polyurethane, polyurea, polytetrafluoroethylene (PTFE), parylene, polypropylene, polystyrene, polyimide, nylon, acetal, ultem, acrylic, epoxy, and phenolic polymers. The embodiments are not limited in this context.

[0030] In various embodiments a second layer 124 of the thin film encapsulant 110 may be disposed on the first layer 122. The first layer 122 and the second layer 124 may together form a first dyad, shown as dyad 120. In various embodiments, the dyad 120 may act as a "functional dyad" where at least one layer of the functional dyad provides a diffusion barrier to contaminants such as moisture and gas species, preventing moisture and gas diffusion through the thin film encapsulant 110. The dyad 120 may also include at least one layer having the properties of being a soft and pliable layer, accommodating changes in dimension of an active device region in a reversible manner. Examples of dyad 120 include a combination of a polymer layer for first layer 122, and a rigid moisture barrier layer such as a rigid dielectric layer or a rigid metal layer for second layer 124, or combinations of rigid metal layer and rigid dielectric layer. A rigid metal layer may include a rigid metal material such as Cu, Al, Pt, Au, or other metal. The embodiments are not limited in this context. In some embodiments, the thin film encapsulant 110 may contain at least one additional dyad, also shown as dyads 120, where the at least one additional dyad is disposed on the first dyad. In the example of FIG. 1B, four dyads are

shown, while the embodiments are not limited in this context. In particular, in other embodiments a thin film encapsulant may include fewer or greater number of dyads. In some examples, a given polymer layer of a dyad may include a plurality of polymer sub-layers, where at least one polymer sub-layer is soft and pliable. Examples of soft and pliable polymer materials 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).

[0031] 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.

[0032] Turning now to **FIG. 2**, there is shown a second instance for operation of the thin film device 100, representing, for example, a second device state of the thin film device 100. In the instance shown in FIG. 2, the thin film device 100 may represent a thin film battery in a charged state. In such a charged state the battery is charged by outdiffusing the diffusant 114, such as lithium, from the source region 104, and transporting the diffusant 114 across intermediate region 106 to accumulate at an anode, represented by the selective expansion region 108. Accordingly, the selective expansion region 108 may be expanded, where the expansion may result in a reduction in thickness of the thin film encapsulant 110 from the first

thickness t_1 as represented by the discharged state of FIG. 1A to a second thickness t_2 as shown in the charged state of FIG. 2. This reduction in thickness at the thin film encapsulant 110 may be the result of the change in thickness of the anode from a third thickness t_3 in the contracted configuration of FIG. 1A to a fourth thickness t_4 in the expanded configuration of FIG. 2. In particular, the growth in thickness of the selective expansion region 108 may displace the thin film encapsulant 110, at least in a region 115, where the region 115 is adjacent the selective expansion region 108. Accordingly, the thin film encapsulant 110 may accommodate the expansion of the selective expansion region 108, by contracting from the thickness t_1 to t_2 as shown in the charged state, representing a second device state, as shown in FIG. 2.

[0033] Configurations where a polymer "layer" or more accurately a polymer layer stack includes multiple polymer sub-layers may provide advantages over configurations having just one polymer layer. For example, a three-layer polymer layer stack may have an inner polymer layer exhibiting soft and pliable properties, and outer polymer layers, where the outer polymer layers are harder and function to distribute stress more uniformly. The harder polymer layers may accordingly reduce localized abnormally high stress points, where such stress points would otherwise cause puncturing of the second layer 124, for example.

[0034] In various embodiments, the first layer 122, meaning the layer immediately adjacent the selective expansion region 108, may be designed to accommodate the entire expansion and contraction or the largest fraction of the expansion or contraction occurring in selective expansion region 108. As detailed below, this accommodation may be accomplished by choice of material or materials for the first layer 122, as well as the detailed architecture of the thin film encapsulant 110.

[0035] In some embodiments, while individual thicknesses (t_1 , t_2 , t_3 and t_4) may change during cycling, the thickness of the at least one polymer layer of thin film encapsulant 110 may be sufficiently large and the polymer layer sufficiently pliable, so as to accommodate the expansion and the contraction taking place during cycling. This accommodation may take place in the following manner. In particular embodiments, during cycling where t_1 and t_2 may represent opposite extremes of thickness, the thickness and pliability of the first layer 122 (or group of layers when first layer 122 is a layer stack) of thin film encapsulant 110 may be result in the following relationship. In particular, the thickness sum of $t_2 + t_4$ is not substantially different from the thickness sum of $t_1 + t_3$, such as a difference of less than 10 %, and in some cases the thickness sum of $t_2 + t_4$ differs from the thickness sum of $t_1 + t_3$ by less than 5 %. In this manner, the pressure on any diffusion barrier layer of the thin film encapsulant 110 is minimized. In some embodiments, the first layer 122 may constitute just one polymer layer accommodating the change in dimension of the selective expansion region 108. In other embodiments, the first layer 122 may constitute multiple polymer sub-layers, where at least one polymer sub-layer, and not necessarily other polymer sub-layers, is soft and pliable. Again, this property of the polymer sub-layer may lead to the thickness sum of $t_2 + t_4$ being not substantially different from the thickness sum of $t_1 + t_3$, such as a difference of less than 10 %. In various embodiments, the thin film encapsulant may have an elongation property of at least 5%.

[0036] Turning now to **FIG. 3** there is shown a thin film battery 300 in accordance with embodiments of the disclosure. The thin film battery 300 may include a substrate base 302, a cathode current collector 304, a cathode 306, a solid state electrolyte 308, an anode 310, and a thin film encapsulant 312, as shown. In various embodiments, the thin film encapsulant 312 may include a plurality of different layers, such as at least one dyad as generally described above. In

particular, the thin film encapsulant 312 may include a layer 314, where the layer 314 is directly disposed on the anode 310. The layer 314 may be formed from a soft and pliable material, as discussed above. In particular, the layer 314 may be a polymer layer, and may include a plurality of polymer-sub-layers in some variants, where the polymer layer, or at least one polymer sub-layer is soft and pliable, as described above. In this manner, the layer 314 may accommodate changes in volume of the anode 310 as the anode 310 increases in thickness or decreases in thickness when the thin film battery 300 charges or discharges. In some embodiments, the thickness of the layer 314 (along the X-axis of the Cartesian coordinate system shown) may be between 10 μm and 50 μm . The embodiments are not limited in this context.

[0037] The thin film encapsulant 312 may further include a layer 316, where the layer 316 is disposed on the layer 314 and is not in direct contact with the anode 310. The layer 316 may be a rigid metal layer as described above, or a rigid dielectric layer composed of a known material such as silicon nitride, where the pliability of the rigid dielectric layer is much less than the pliability of layer 314. According to various embodiments, a rigid dielectric layer may have a combination of relatively high elastic modulus and hardness, for example. In the case of silicon nitride, the Vicker's hardness is ~ 13 GPa, and Young's Modulus is ~ 43500 Kpsi or ~ 300 GPa). Accordingly, the rigid dielectric layer is less pliable than at least one polymer layer of the layer 314. Similarly, known metals having a Vicker's hardness as well as Young's modulus in excess of the values for polymer materials shown above may be used as layer 316.

[0038] The layer 316 may serve as a diffusion barrier layer, to prevent diffusion of ambient species such as H_2O (moisture) from outside the thin film battery 300 from penetrating to active device regions of the thin film battery 300, including the anode 310, solid state electrolyte 308, and cathode 306, for example. In some embodiments, the layer 316 may have a

thickness of 0.25 μm to 1 μm . The layer 316 may in some variants include a plurality of rigid dielectric layers or rigid metal layers, or combinations thereof. The embodiments are not limited in this context. The layer 314 and layer 316 may together constitute a dyad, where a dyad is composed of a soft and pliable layer or layers, and a rigid dielectric layer or rigid metal layer. As illustrated in FIG. 3, the thin film encapsulant 312 may include a plurality of dyads. For example, a layer 318 is disposed on the layer 316, where the layer 318 may be a soft and pliable layer, which layer may include a plurality of polymer-sub-layers in some variants, while a layer 320 is disposed on the layer 318, where the layer 320 may be a rigid dielectric or rigid metal layer or set of layers. Accordingly, the layer 318 and layer 320 may be deemed to be a second dyad. This sequence of alternating between a soft and pliable layer and a rigid dielectric layer may be repeated, as represented, for example by layer 322 and layer 324.

[0039] In various other embodiments, a thin film encapsulant may include any number of layers, where a first layer immediately adjacent the selective expansion region of a thin film battery or other electrochemical device, is a soft and pliable layer or includes at least one soft and pliable sub-layer. At the same time a second layer disposed on the first layer is a rigid dielectric or rigid metal layer or set of layers. These configurations provide advantages over known thin film encapsulants using a rigid dielectric immediately adjacent an anode region, for example. Firstly, the thin film encapsulant 312 provides the diffusion barrier properties imparted by a rigid dielectric or rigid metal layer by virtue of incorporation of at least one rigid dielectric or rigid metal layer in a dyad composed of a soft and pliable layer in combination with a rigid dielectric layer or rigid metal layer. Additionally, because the first layer adjacent the selective expansion region is a soft and pliable layer (whether a polymer or other soft and pliable layer), the volume expansion is more easily accommodated during a charging cycle when diffusant moves into the

selective expansion region (anode region). The volume expansion is especially more easily accommodated as compared to batteries configured with known thin film encapsulants where a rigid dielectric or rigid metal layer is adjacent the anode. In particular, the first layer may elastically deform to accommodate volume changes in an anode region, and may prevent cracks, delamination, or other damage from occurring in the thin film encapsulant, where such damage may otherwise occur in thin film encapsulants where an inflexible, rigid dielectric is disposed adjacent the anode. In this manner, a thin film encapsulant such as thin film encapsulant 312 may remain intact after an anode is charged to allow continued protection of the active device from attacks by ambient oxidants, where such ambient oxides would otherwise permeate through a breached thin film encapsulant.

[0040] Moreover, by providing a soft and pliable first layer adjacent the anode region, during an opposite cycle of discharging the soft and pliable first layer may expand back to release the stress and to "fill a void" where the void would otherwise occur when the diffusant (such as lithium) migrates back to a cathode. By "filling the void" when the soft and pliable first layer expands into the region being vacated by diffusant species returning to the cathode, the electrical contacts in the anode may be enhanced. This enhancement may provide longer term stability including electrical and electrochemical performance, such as stable contact resistance at the anode (selective expansion region) between the anode and electrolyte.

[0041] In accordance with various embodiments, a thin film encapsulant, such as the thin film encapsulant 312, may comprise materials having the property of being laser-etchable, and in particular may include a layer absorbent to laser radiation over a target wavelength range provided a laser. In a thin film encapsulant containing a laser-etchable material, electromagnetic radiation of a given wavelength of a laser beam is highly absorbed in the thin film encapsulant.

Examples of suitable radiation wavelengths include the range from 157 nm to 1064 nm. For example, for a laser beam having a wavelength in the visible range, a transparent or completely clear-appearing polymer layer may not be highly absorbent of the electromagnetic radiation of the laser beam. For the same laser beam having wavelength in the visible range, an opaque, black, or translucent polymer layer may be highly absorbent of the electromagnetic radiation, and may accordingly be deemed a laser-etchable material. The embodiments are not limited in this context.

[0042] This property facilitates maskless patterning of the thin film encapsulant 312, where a laser is used to ablate portions of the thin film encapsulant 312 in target regions. For example, the thin film encapsulant 312 may include rigid dielectric or rigid metal layers (such as layer 316, layer 320, and layer 324) formed from silicon nitride or similar material, or a rigid metal layer, such as Cu, (or Cu). In these materials strong electromagnetic radiation absorption may take place in the wavelength range of 157 nm to 1064 nm to accommodate processing by known lasers generating radiation in at least a portion of the aforementioned wavelength range. Similarly, the layer 314, layer 318, and layer 322 may be formed of a polymer, where the polymer also strongly absorbs electromagnetic radiation over a similar wavelength range. Accordingly, a thin film encapsulant may be patterned as shown in FIG. 3, where the thin film encapsulant 312 conformally coats an active device region 330 to form a thin film battery, while being isolated from other structures by the region 340, formed by laser etching of the layers of the thin film encapsulant 312. In particular embodiments, the etchability of known polymer materials used in the thin film encapsulant 312 may be enhanced as needed where such polymer materials may have relatively lower absorption of laser radiation. For example, a known polymer such as silicone may have etchability enhanced by adding a dye to the polymer to

increase radiation absorption, or may be placed between two layers, where the two layers are more highly etchable by a given laser.

[0043] Turning now to **FIG. 4** there is shown a thin film battery 400 in accordance with other embodiments of the disclosure. The thin film battery 400 may include a substrate base 302, a cathode current collector 304, a cathode 306, a solid state electrolyte 308, and an anode 310, as described above with respect to FIG. 3. The illustration in FIG. 4 may represent a discharged state of the thin film battery 400. The thin film battery 400 also includes thin film encapsulant 412, as shown. In various embodiments, the thin film encapsulant 412 may include a plurality of different layers, such as at least one dyad as generally described above with respect to FIG. 3. In the architecture shown in FIG. 4, the thin film encapsulant 412 includes a first layer, shown as layer 414. The layer 414 is disposed immediately adjacent the anode 310 and is made of a soft and pliable material, such as a polymer, or may include multiple sub-layers, where at least one sub-layer of layer 414 is soft and pliable. In some embodiments of the thin film encapsulant 412 illustrated in FIG. 4, the layer 414 may be composed of a similar material as in layer 318 and layer 322.

[0044] According to some embodiments the layer thickness may vary among different layers of a thin film encapsulant. A hallmark of the thin film encapsulant 412 is the relative thickness of the layer 414. In particular, the thickness of the layer 414 may be designed to accommodate a large fraction, if not all, of the volume change taking place in anode 310 when the thin film battery 400 charges and discharges. The thickness of the layer 414 may be designed to be greater than the thickness of other layers in the thin film encapsulant 412. For example, the thickness of layer 414 may be between 20 μm and 50 μm , while the thickness of the rigid dielectric or rigid metal layers, layer 316, layer 320, and layer 324 is 5 μm or less. Moreover,

the thickness of additional soft and pliable layers of the thin film encapsulant 412, such as layer 318 and layer 322, may be 20 μm or less. The embodiments are not limited in this context. Altogether, in some embodiments the thickness of the device stack 420, including the active device region 330 and thin film encapsulant 412 may be approximately 80 to 120 μm , and in some embodiments may be 50 to 80 μm . The embodiments are not limited in this context.

[0045] Turning now to **FIG. 5**, there is shown another depiction of the thin film battery 400, representing a charged state. As noted previously, in Li thin film batteries where a cathode is a solid state cathode formed from LiCoO_2 having a thickness 15 μm to 17 μm thick, the amount of lithium transported between cathode and anode during charging may be the equivalent of a 6 μm layer of Li. Accordingly, by arranging a first layer of a thin film encapsulant 412 to be soft and pliable and to have thickness in the range up to 50 μm , such an increase in thickness in the anode 310 may be more easily accommodated while not causing cracking, delamination or other problems. At the same time, the thickness of the additional layers of the thin film encapsulant 412, including additional soft and pliable layers, may be maintained at relatively lower values, because most or all of the deformation in the anode 310 may be accommodated by the reversible elastic deformation in the first layer. This circumstance is illustrated in FIG. 5, where the layer 414 is elastically compressed along the Z-axis (compare with FIG. 4), while the other layers of the thin film encapsulant 412 are not compressed or otherwise damaged, maintaining their original dimensions with little or no stress. In particular embodiments, during cycling where t_1 and t_2 may represent opposite extremes of thickness for thin film encapsulant 412, the thickness and pliability of the layer 414 of thin film encapsulant 412 may result in the following. The thickness sum of $t_2 + t_4$ (shown as t_6 in FIG. 5)

may be not substantially different from the thickness sum of $t_1 + t_3$, (shown as t_5 in FIG. 4) such as a difference of less than 10 %.

[0046] In this manner, the thin film battery 400 may provide an improved performance compared to known thin film batteries by providing the following features. Firstly, multiple rigid dielectric or rigid metal layers are provided to act as diffusion barriers. Secondly, a layer, the "first layer," is provided immediately adjacent to an anode to directly absorb the deformation in the anode caused during charging and discharging of the battery, all within a compact device structure (50 μm - 100 μm). By absorbing all or most of the deformation of a subjacent layer or layers within an active device within the first layer of a thin film encapsulant, the first layer may prevent the remaining layers including diffusion barriers from deformation, or may greatly reduce the deformation of such layers.

[0047] There are multiple advantages provided by the present embodiments, including the ability to reduce the thickness of non-active packaging materials such as thin film encapsulants used in a thin film device, leading to enhanced energy density of these devices. A further advantage lies in improving the robustness ability of a thin film device encapsulant, where the thin film device is patternable by a maskless process.

[0048] 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 device, comprising:

an active device region, the active device region comprising a diffusant; and

a thin film encapsulant disposed adjacent to the active device region and encapsulating at least a portion of the active device region, the thin film encapsulant comprising:

a first layer, the first layer disposed immediately adjacent the active device region and comprising a soft and pliable material; and

a second layer disposed on the first layer, the second layer comprising a rigid dielectric material or rigid metal material.
2. The thin film device of claim 1, wherein the active device region comprises:

a source region comprising the diffusant; and

a selective expansion region, the selective expansion region being disposed immediately adjacent the first layer, wherein transport of the diffusant takes place reversibly between the source region and the selective expansion region.
3. The thin film device of claim 2, wherein the source region comprises a solid state cathode, and wherein the selective expansion region comprises an anode.
4. The thin film device of claim 3, wherein the thin film encapsulant comprises a first thickness in a first device state and a second thickness in a second device state, wherein the anode comprises a third thickness in the first device state and a fourth thickness in the second device state, wherein the third thickness is less than the fourth thickness by at least 1 μm .

5. The thin film device of claim 1, wherein the first layer comprises a polymer layer, the polymer layer further comprising a polymer layer stack including at least one sub-layer.
6. The thin film device of claim 1, the first layer comprising at least one of: a getter/absorbent infused silicone, a porous low dielectric constant material, a silver paste, and epoxy, a printed circuit board material, a photo-resist material, silicone, rubber, urethane, polyurethane, polyurea, polytetrafluoroethylene, parylene, polypropylene, polystyrene, polyimide, nylon, acetal, ultem, acrylic, epoxy, and phenolic a polymer, or combination thereof.
7. The thin film device of claim 1, the first layer and the second layer together forming a first dyad, wherein the thin film encapsulant comprises at least one additional dyad, the at least one additional dyad being disposed on the first dyad.
8. The thin film device of claim 1, wherein the second layer comprises a diffusion barrier layer, the diffusion barrier layer preventing moisture and gas diffusion through the thin film encapsulant.
9. The thin film device of claim 1, wherein the second layer comprises silicon nitride, Cu, or Al.
10. The thin film device of claim 1, wherein the second layer comprises a thickness of 0.25 μm to 5 μm .

11. The thin film device of claim 1, wherein the first layer and second layer together constitute a dyad, wherein the thin film encapsulant comprises a plurality of dyads, wherein the first layer comprises at least one sub-layer.

12. The thin film device of claim 1, further comprising a substrate base, wherein the active device region and the thin film encapsulant are disposed on the substrate base, wherein the active device region and thin film encapsulant together form a device stack, wherein a thickness of the device stack is 120 μm or less.

13. A thin film battery, comprising:

an active device region, the active device region comprising:

a lithium-containing cathode; and

a solid state electrolyte, disposed on the cathode;

an anode disposed on the solid state electrolyte; and

a thin film encapsulant disposed adjacent to the anode and encapsulating at least a portion of the lithium-containing cathode, the solid state electrolyte, and the anode, the thin film encapsulant comprising:

a first layer, the first layer disposed immediately adjacent the active device region and comprising a soft and pliable material; and

a second layer disposed on the first layer, the second layer comprising a rigid dielectric material or rigid metal material.

14. The thin film battery of claim 13, wherein the thin film encapsulant comprises a layer absorbent to laser radiation over a wavelength range of 157 nm to 1064 nm.

15. The thin film battery of claim 13, the first layer and the second layer together forming a first dyad, wherein the thin film encapsulant comprises at least one additional dyad, the at least one additional dyad being disposed on the first dyad.

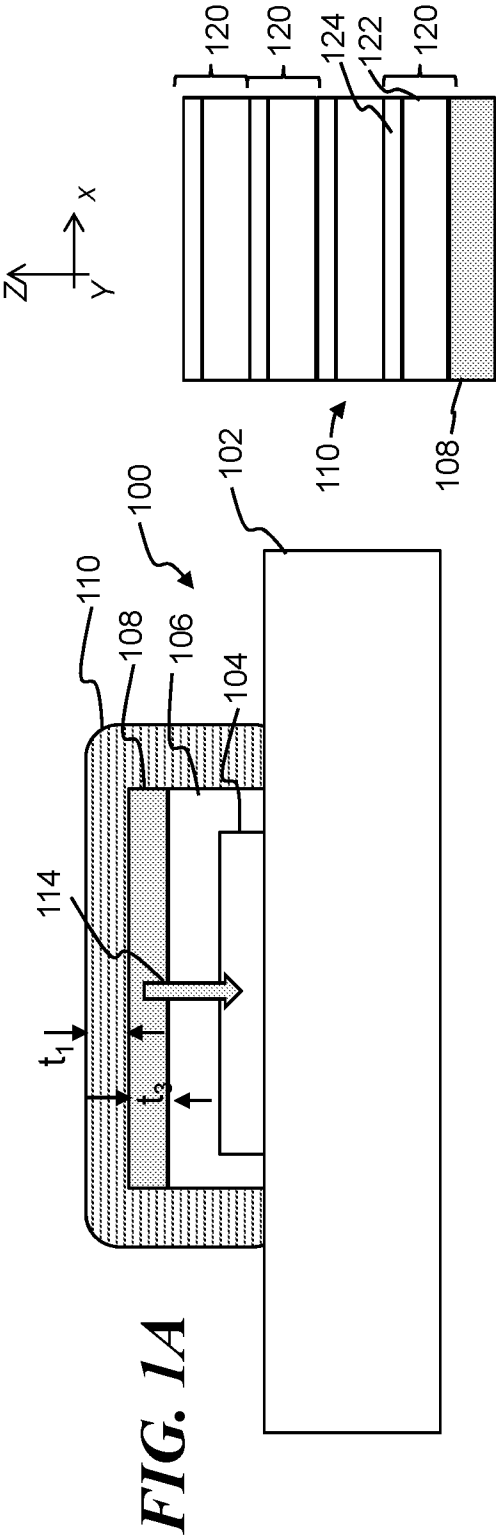


FIG. 1B

