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Deng et al.

(54) FOLDABLE SUBSTRATES, FOLDABLE ARTICLES, AND METHODS OF MAKING THE SAME

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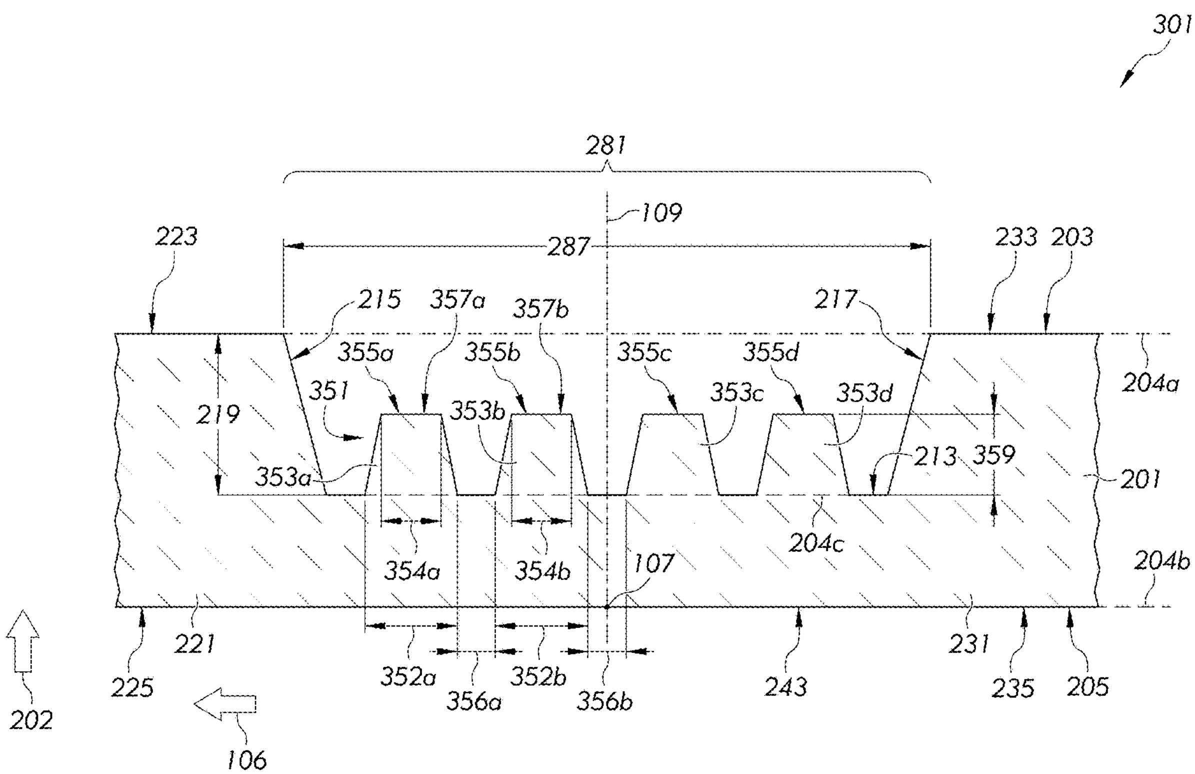
(57) **ABSTRACT**

Foldable substrates have a first portion, a second portion, and a central portion positioned therebetween. The first portion and the second portion have a substrate thickness less than a central thickness of the central portion. A plurality of protrusions extend from a first central surface area of the central portion. A total protrusion area is a sum of an area of an upper surface of each protrusion of the plurality of protrusions. A total central area is an area of the central portion. An area ratio of the total protrusion area to the total central area is from 0.10 to 0.70. Methods include disposing a patterned mask on an initial major surface of a foldable substrate and then etching the foldable substrate to form the plurality of protrusions.



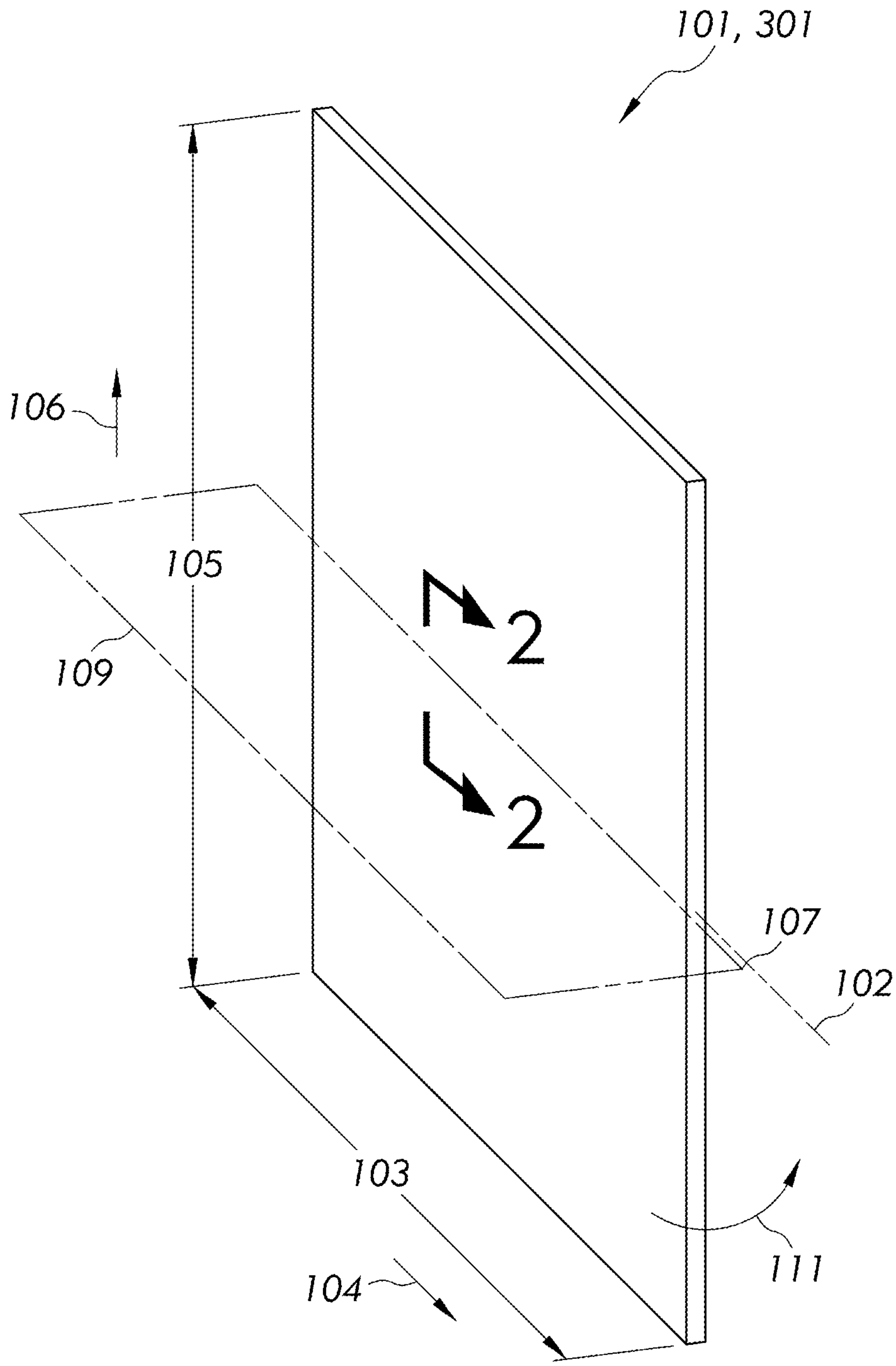
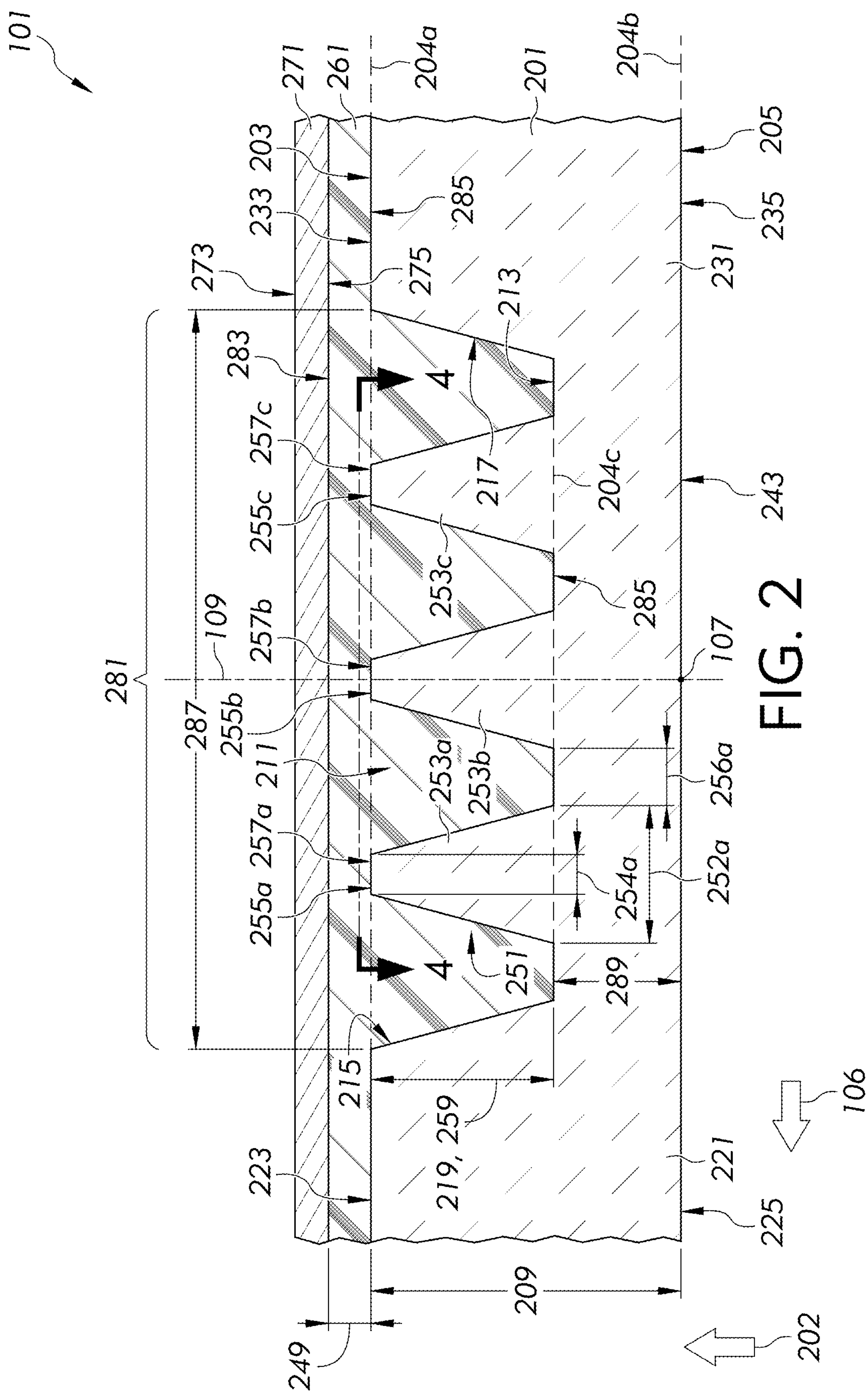


FIG. 1


101
271
261
204a
201
204b
205
203
285
233
235
273
275
231
213
283
4
257c
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204c
243
255c
253c
285
109
257b
107
281
287
255b
211
253a
253b
256a
257a
254a
252a
255a
4
251
289
215
219, 259
106
223
221
225
209
249
202

FIG. 2

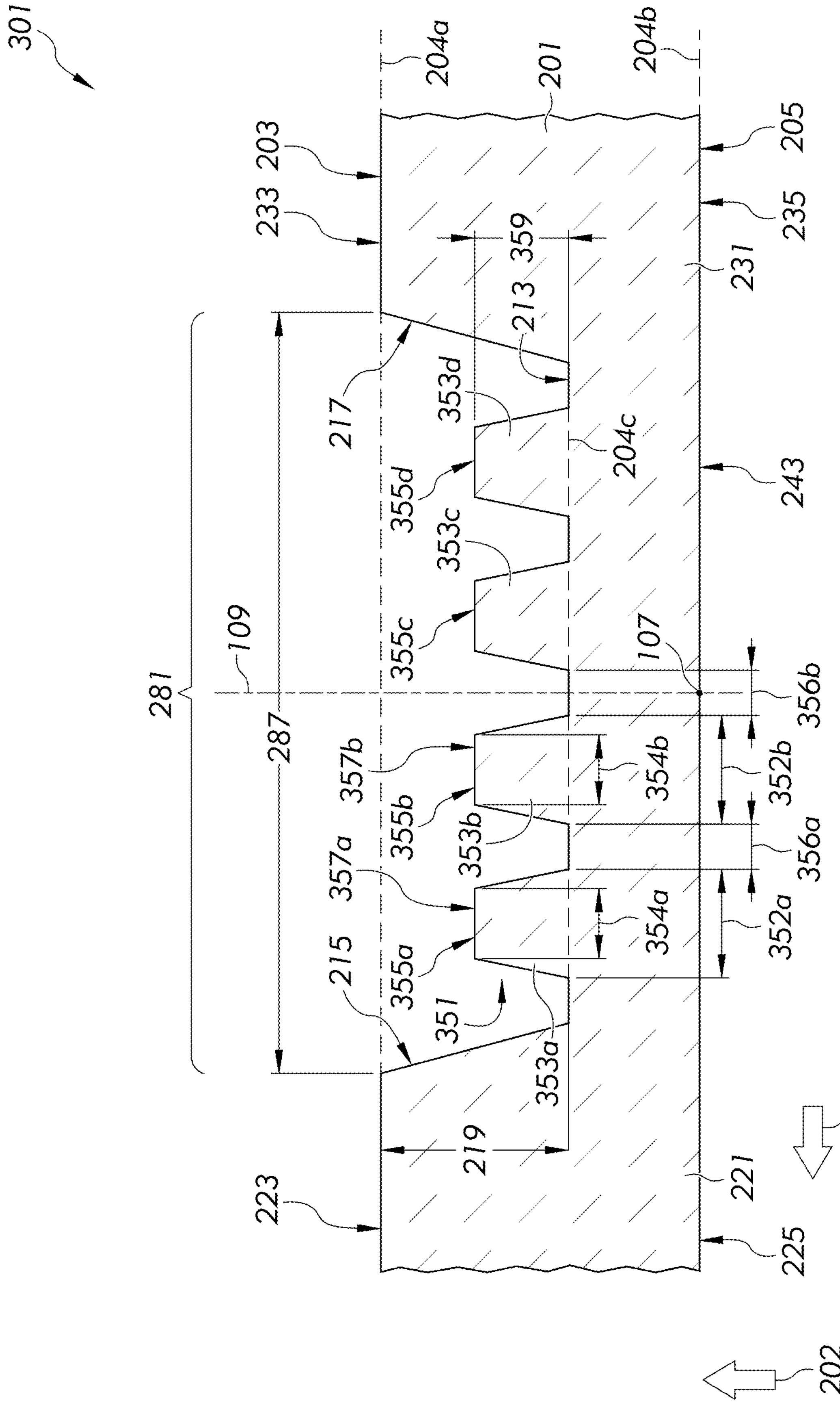

301
204a
201
204b
203
205
233
235
359
213
231
217
353d
204c
355d
243
353c
109
107
281
355c
287
356b
357b
354b
355b
352b
353b
356a
357a
354a
352a
215
355a
351
353a
219
106
221
223
225
202

FIG. 3

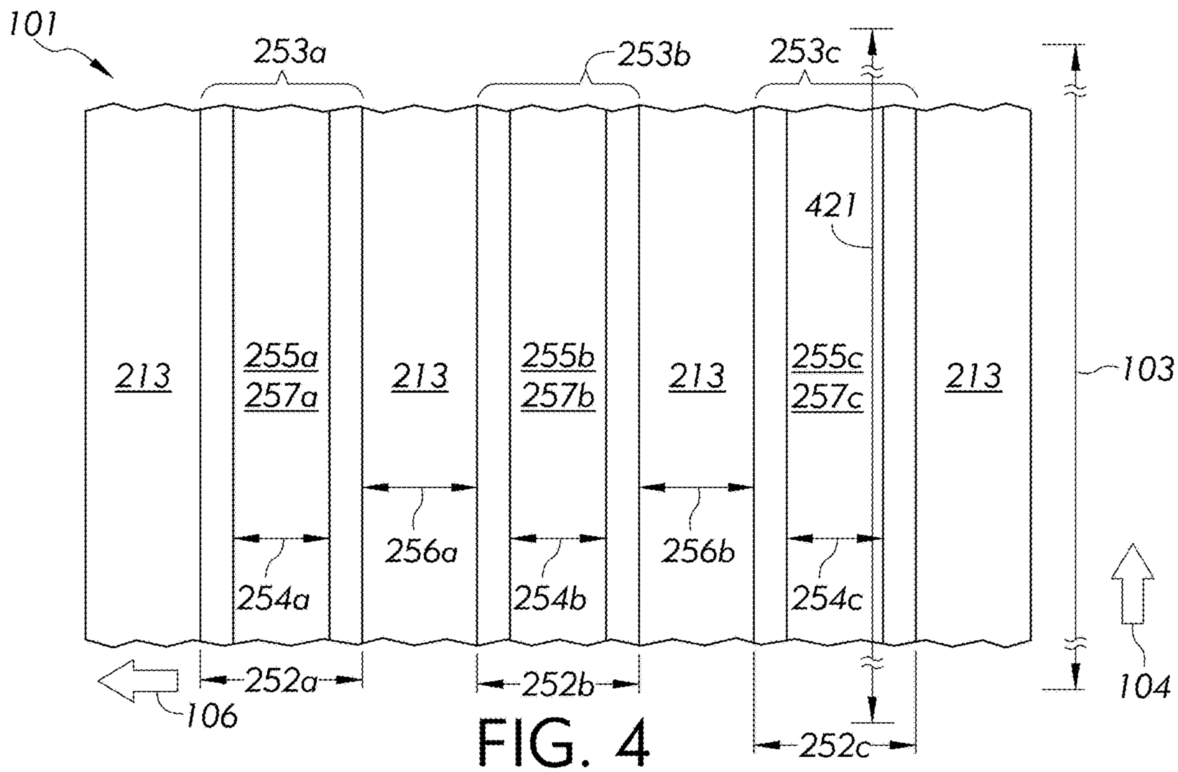

101
253a
253b
253c
421
213
255a
257a
255b
257b
255c
257c
103
256a
256b
254a
254b
254c
104
252a
252b
252c
106

FIG. 4

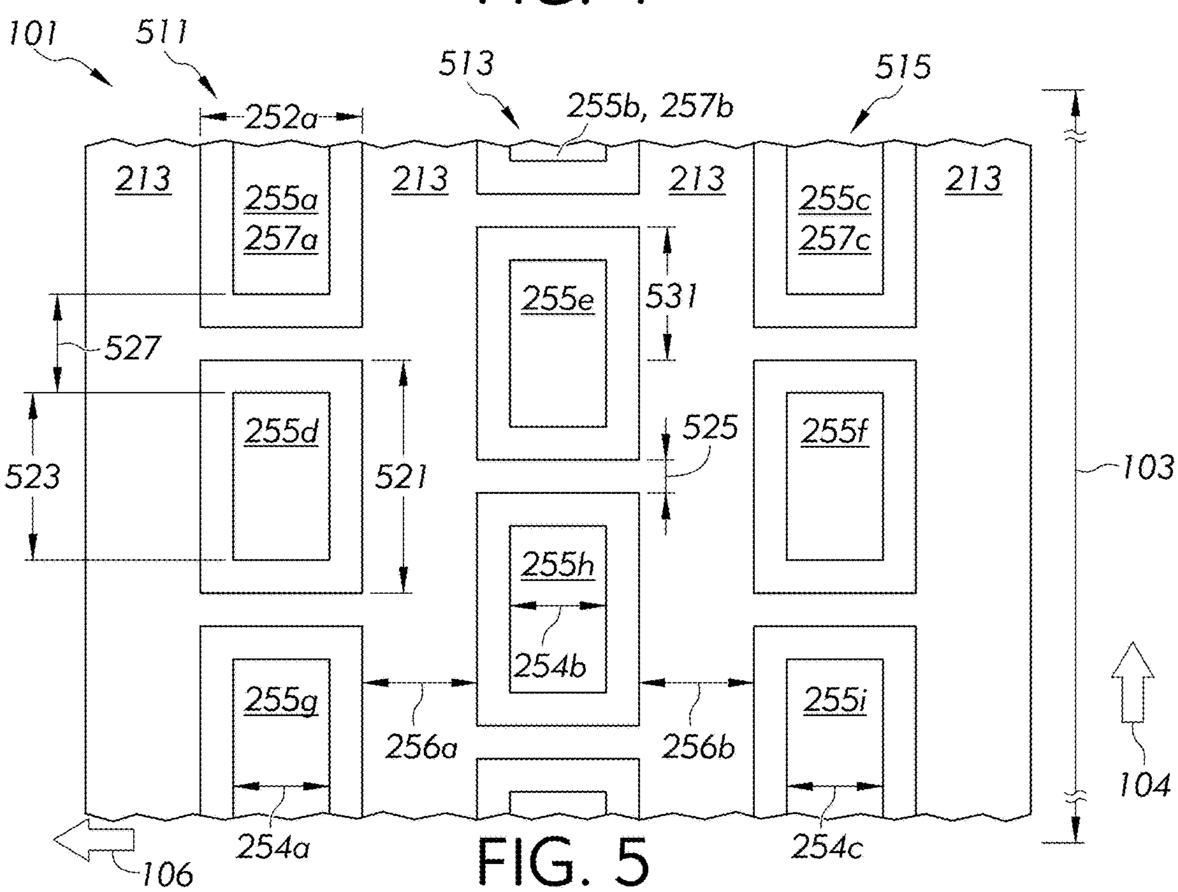

101
511
513
515
252a
255b, 257b
213
255a
257a
255c
257c
255e
531
527
525
255d
255f
523
521
103
255h
254b
255g
255i
256a
256b
104
254a
254c
106

FIG. 5

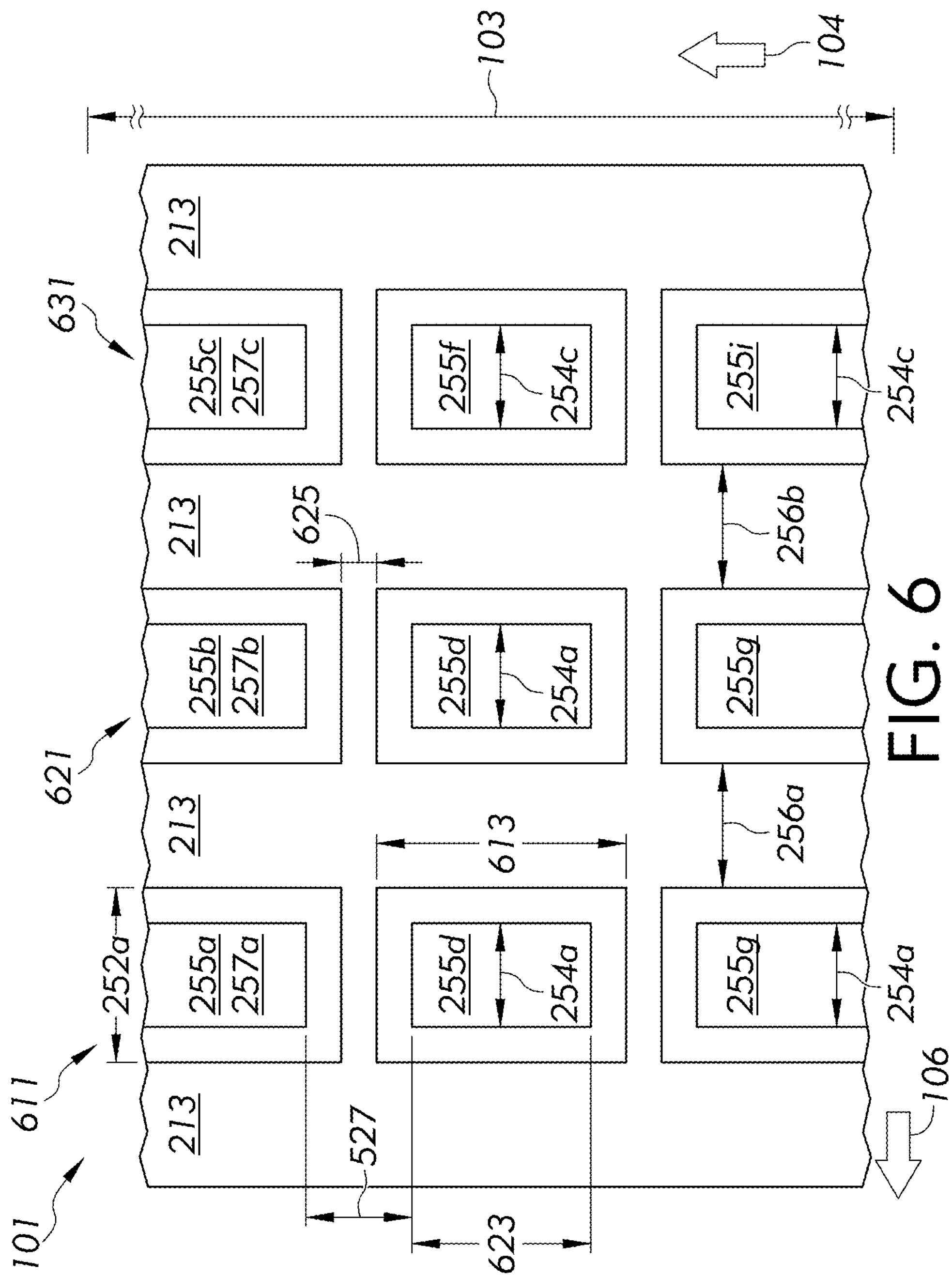

103
104
213
631
255c
257c
255f
254c
255i
254c
213
625
256b
255b
257b
255d
254a
255g
621
213
613
256a
252a
255a
257a
255d
254a
255g
254a
611
213
106
101
527
623

FIG. 6

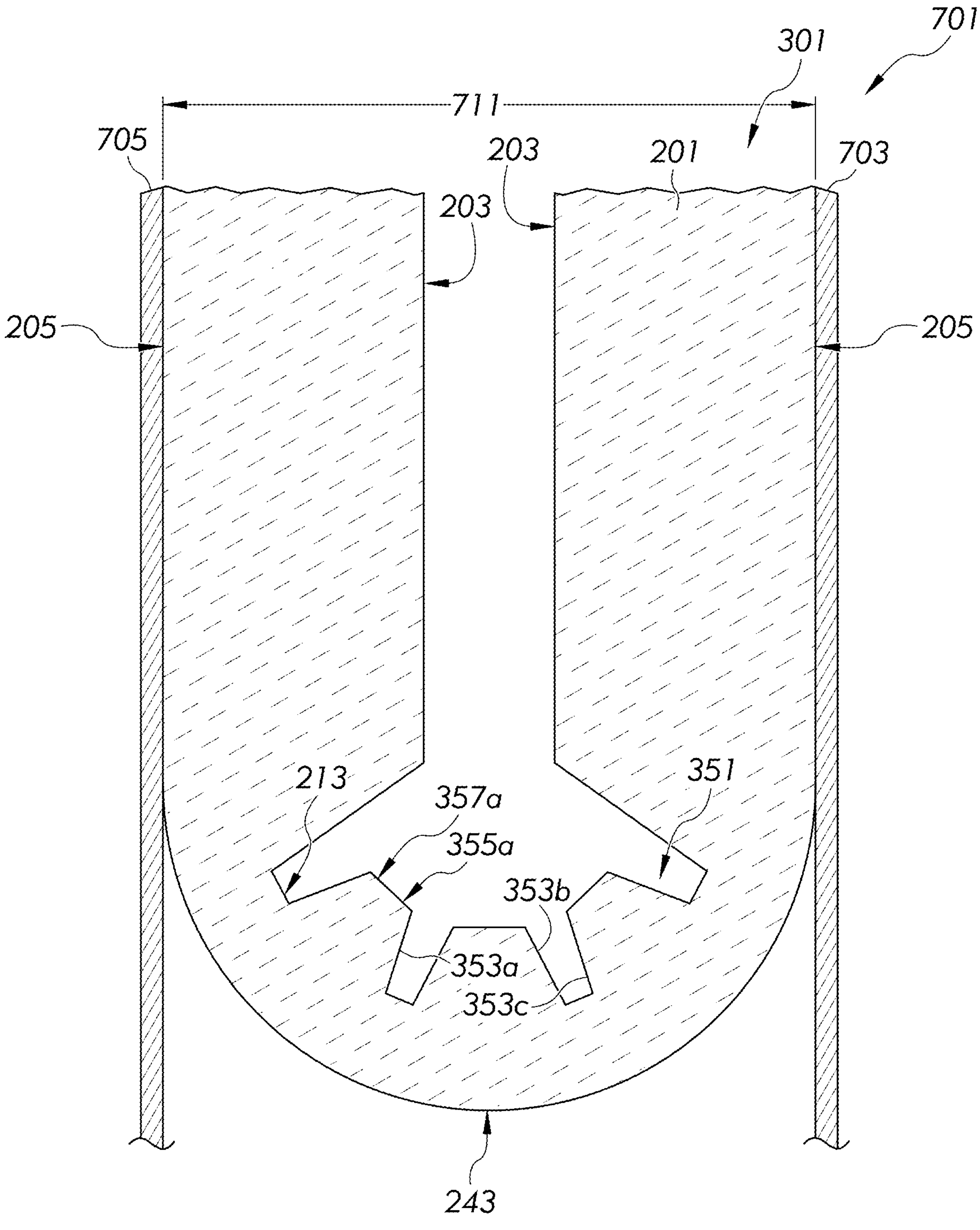

701
301
711
705
203
201
703
203
205
205
213
357a
351
355a
353b
353a
353c
243

FIG. 7

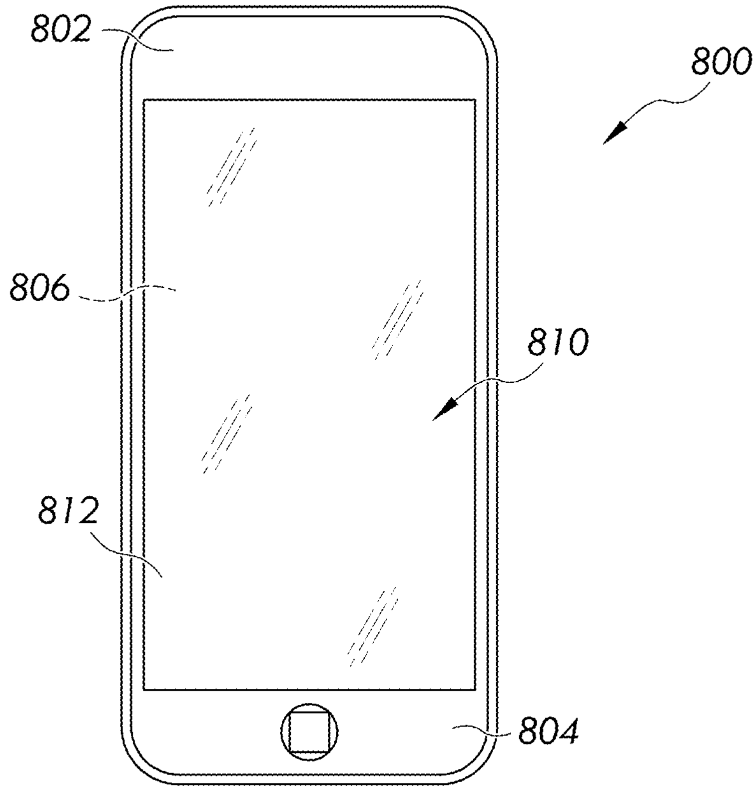


FIG. 8

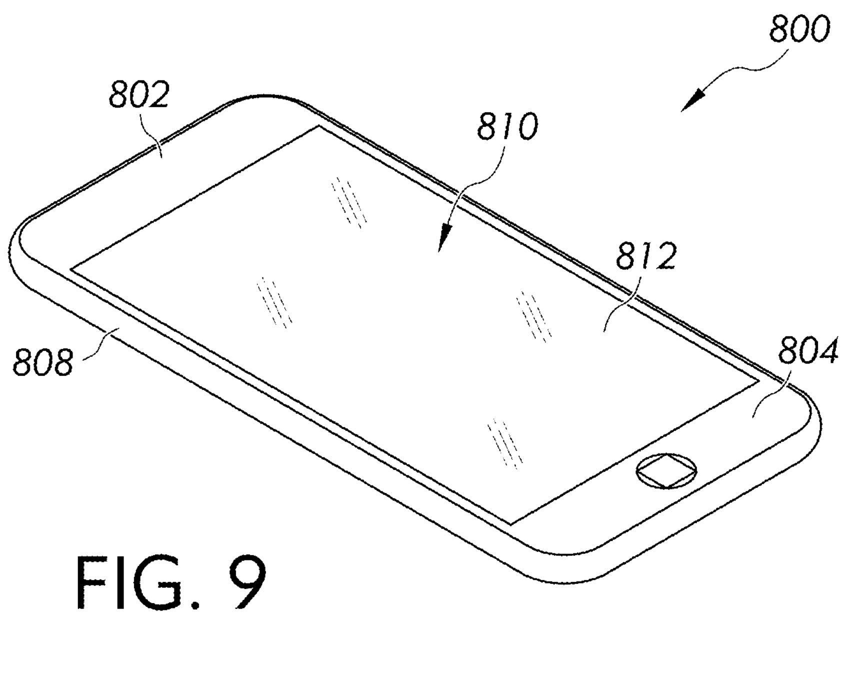
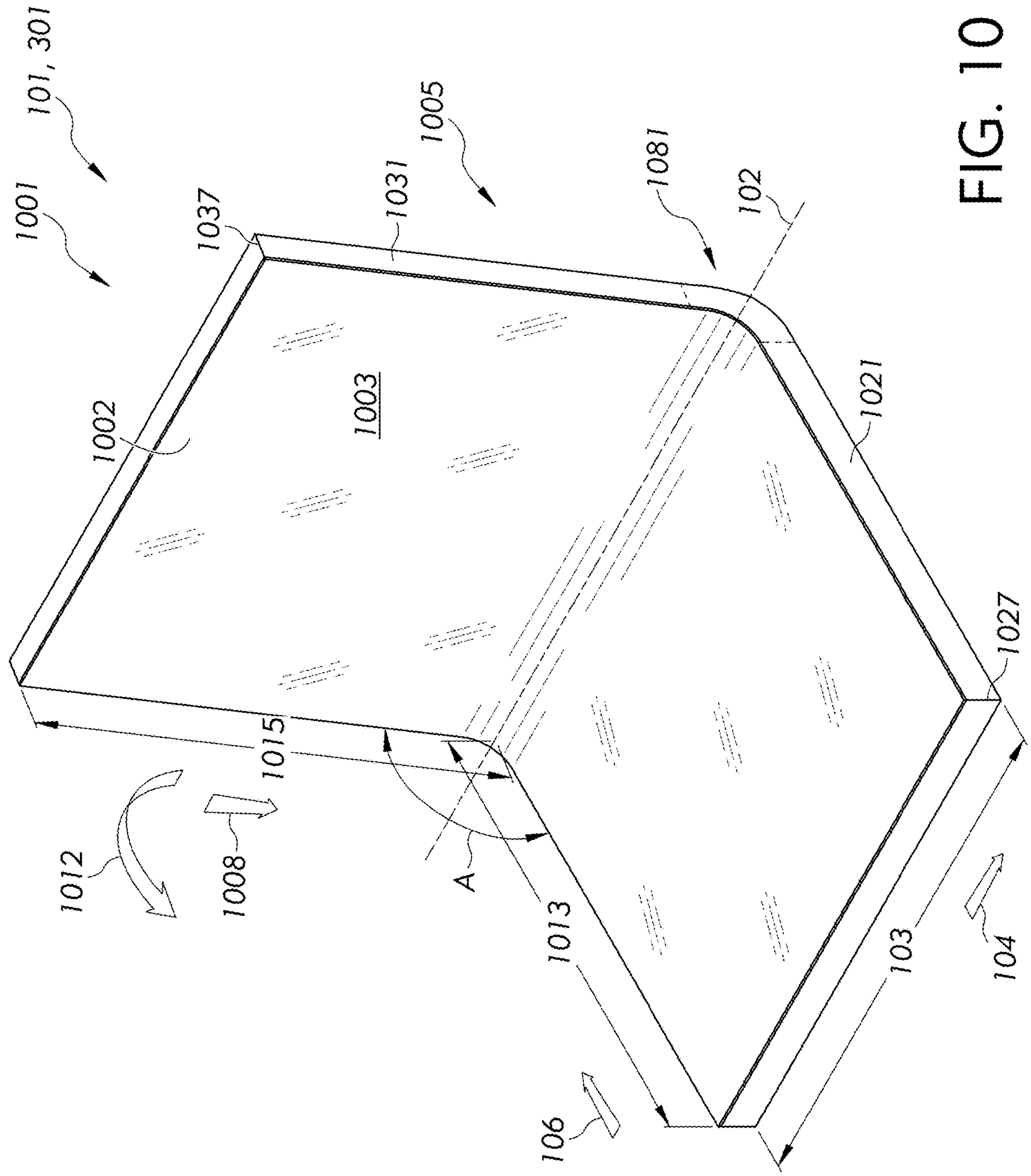


FIG. 9



101, 301
1001
1005
1037
1031
1081
102
1002
1003
1021
1027
1015
1012
1008
A
1013
103
104
106

FIG. 10

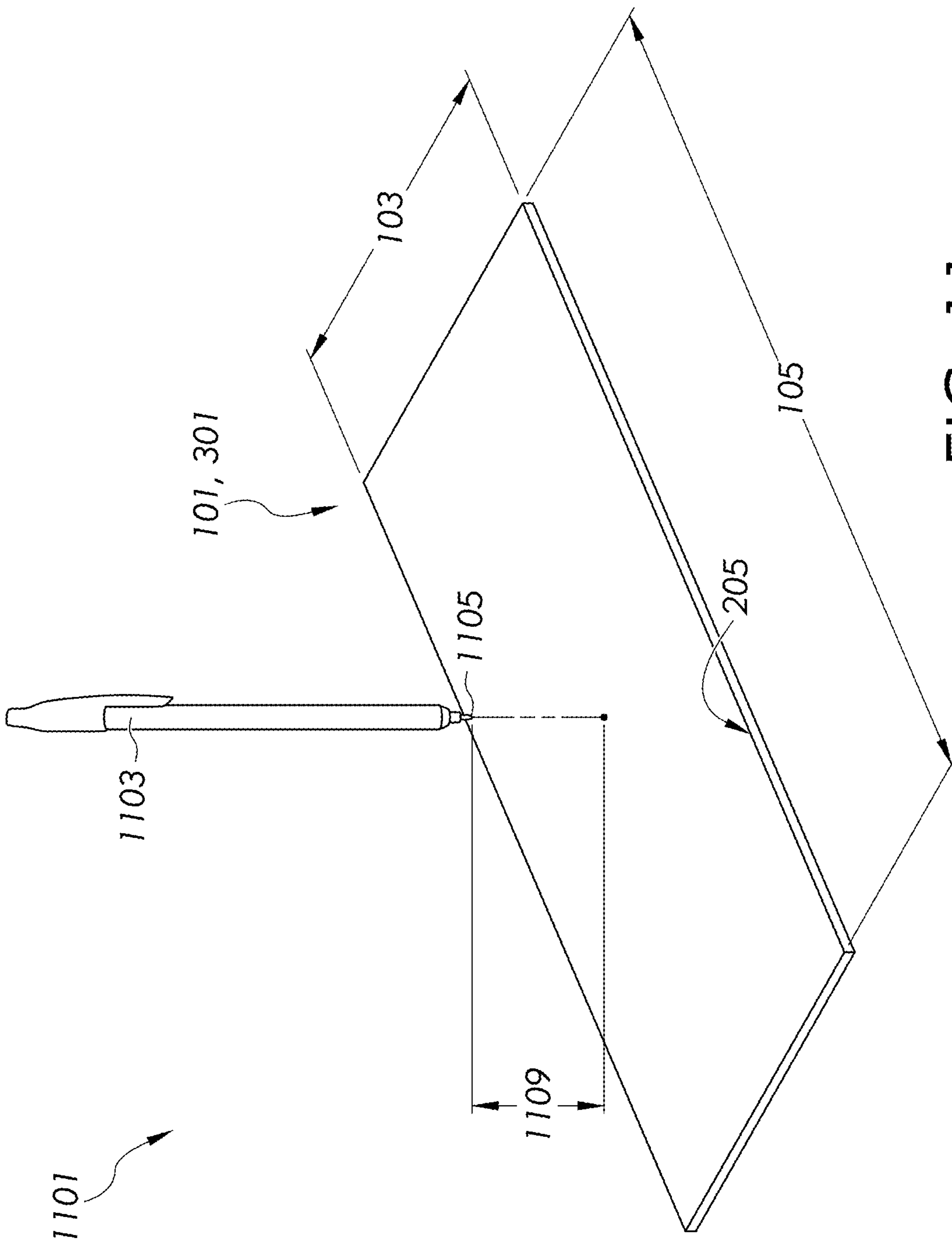


FIG. 11

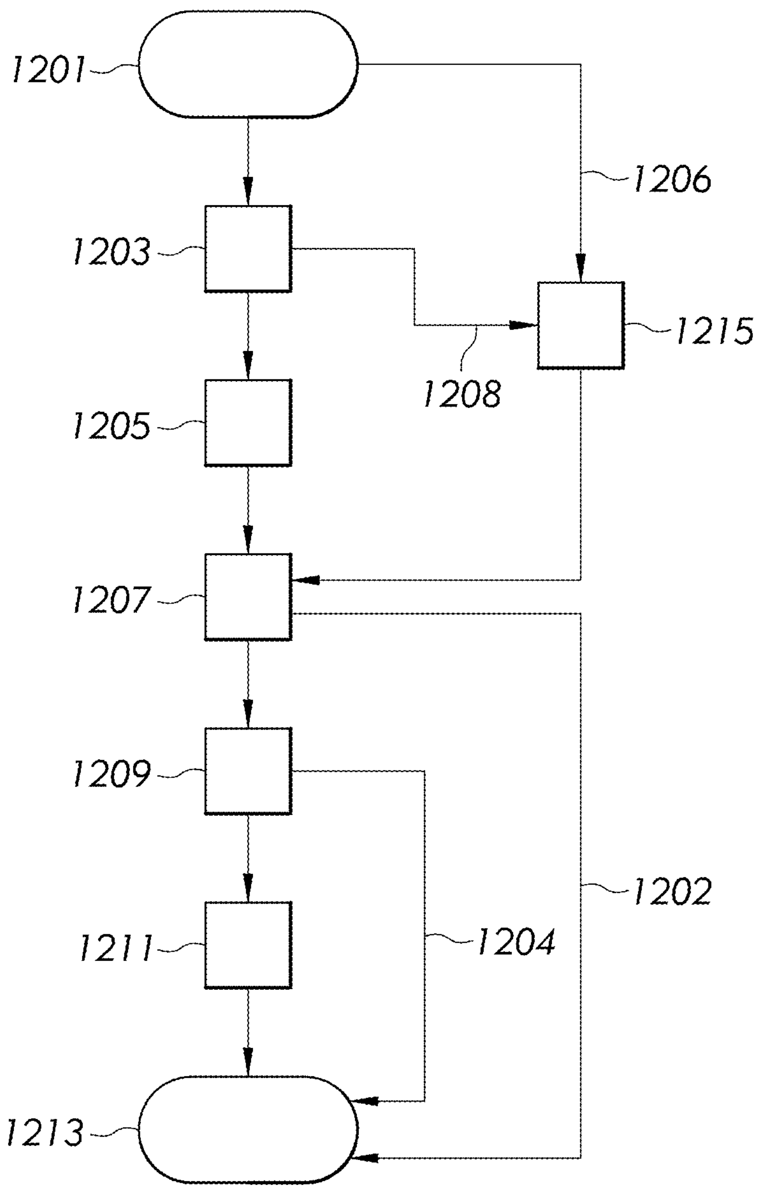


FIG. 12

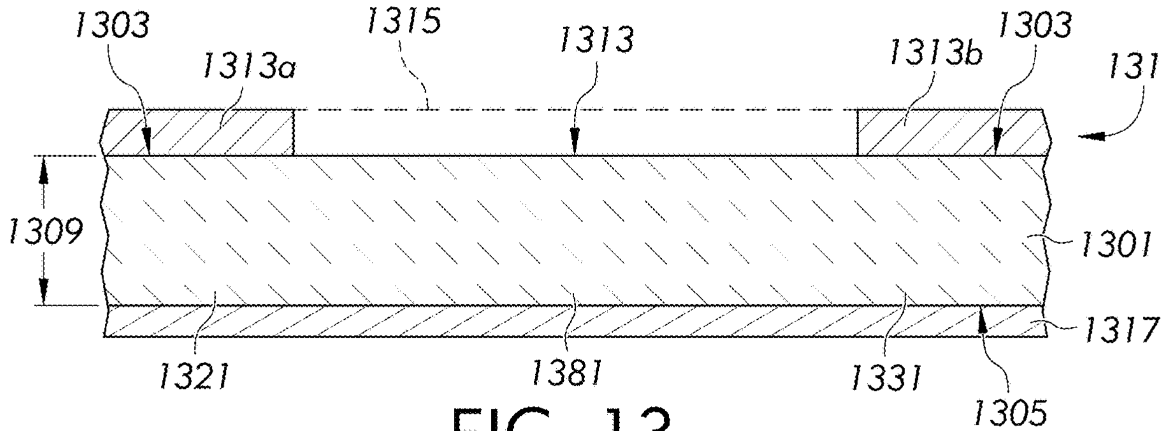


FIG. 13

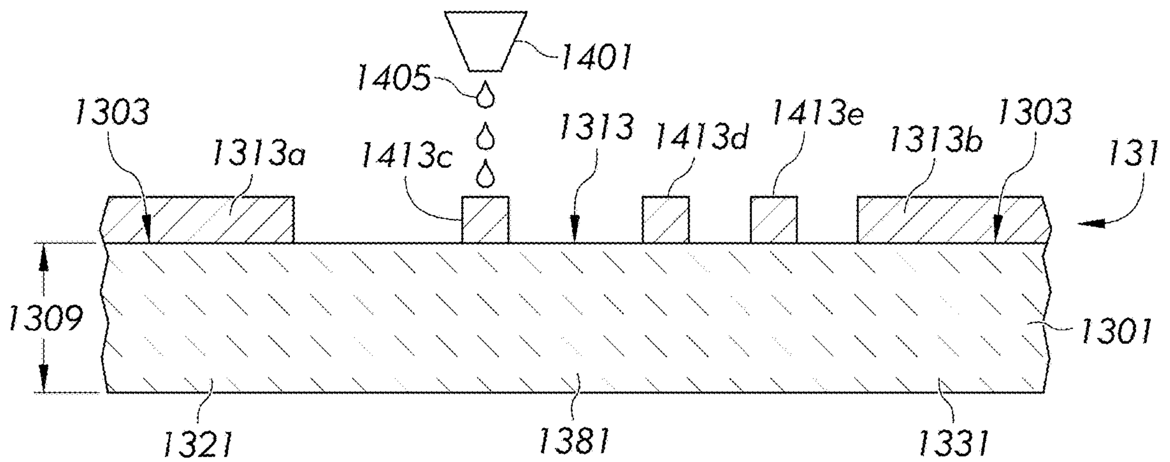


FIG. 14

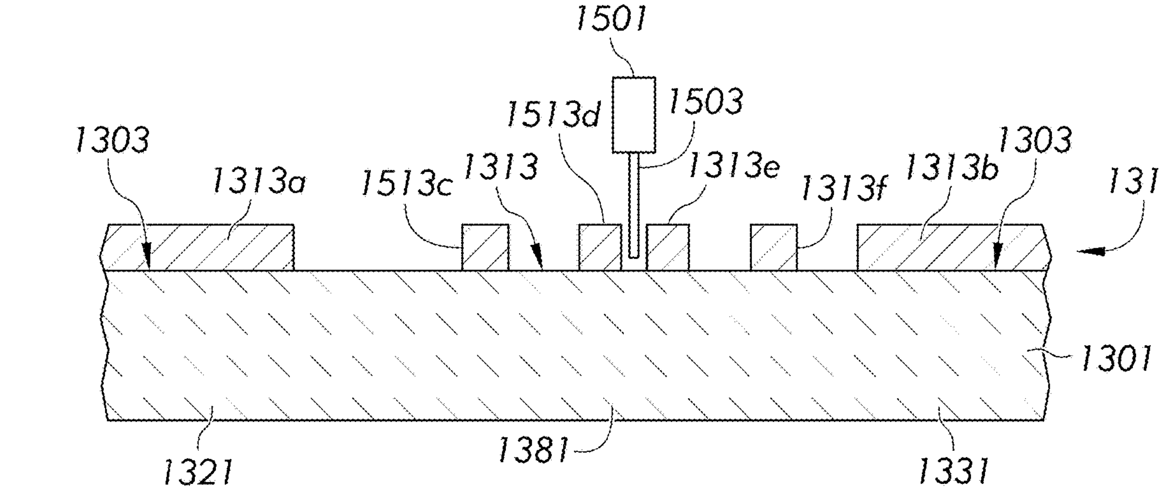


FIG. 15

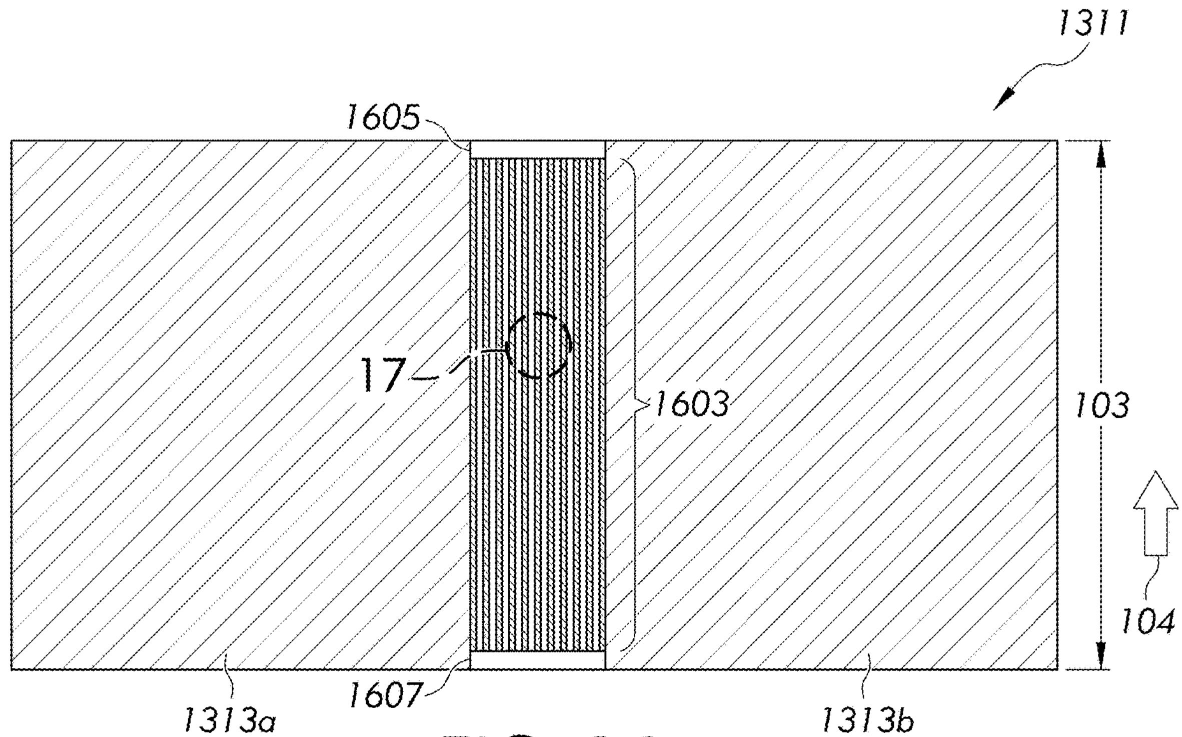

1311
1605
17
1603
103
104
1607
1313a
1313b

FIG. 16

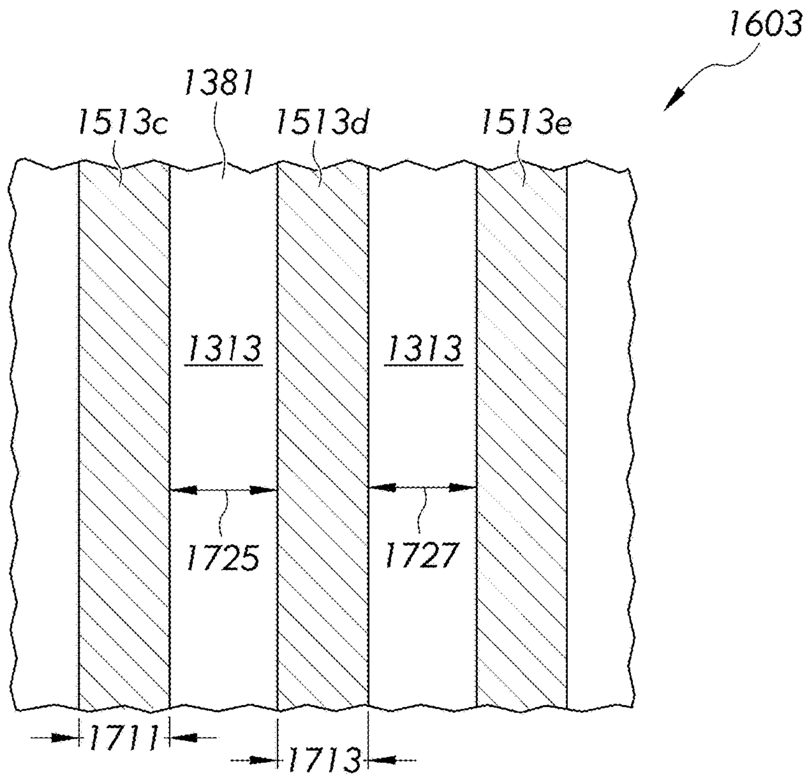

1603
1381
1513c
1513d
1513e
1313
1313
1725
1727
1711
1713

FIG. 17

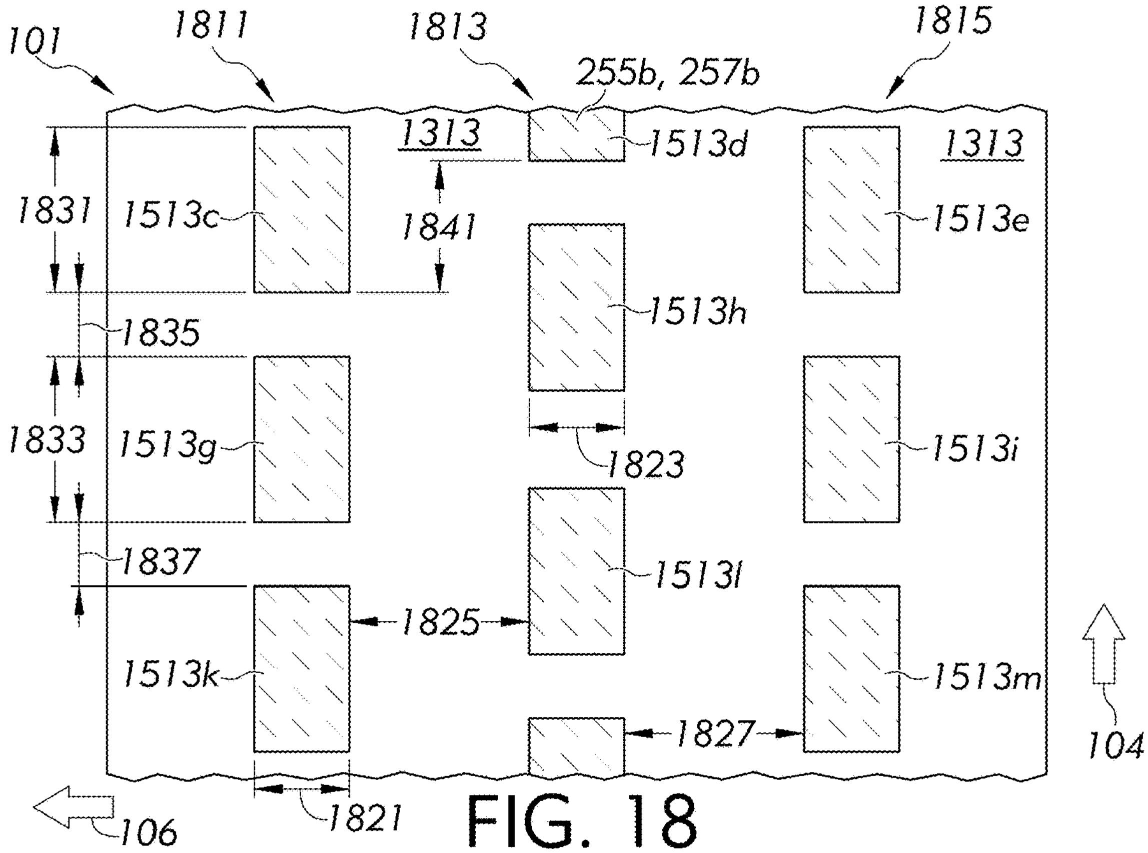

101
1811
1813
1815
255b, 257b
1313
1513d
1313
1831
1513c
1841
1513e
1513h
1835
1833
1513g
1823
1513i
1837
1513l
1825
1513k
1513m
1827
104
1821
106

FIG. 18

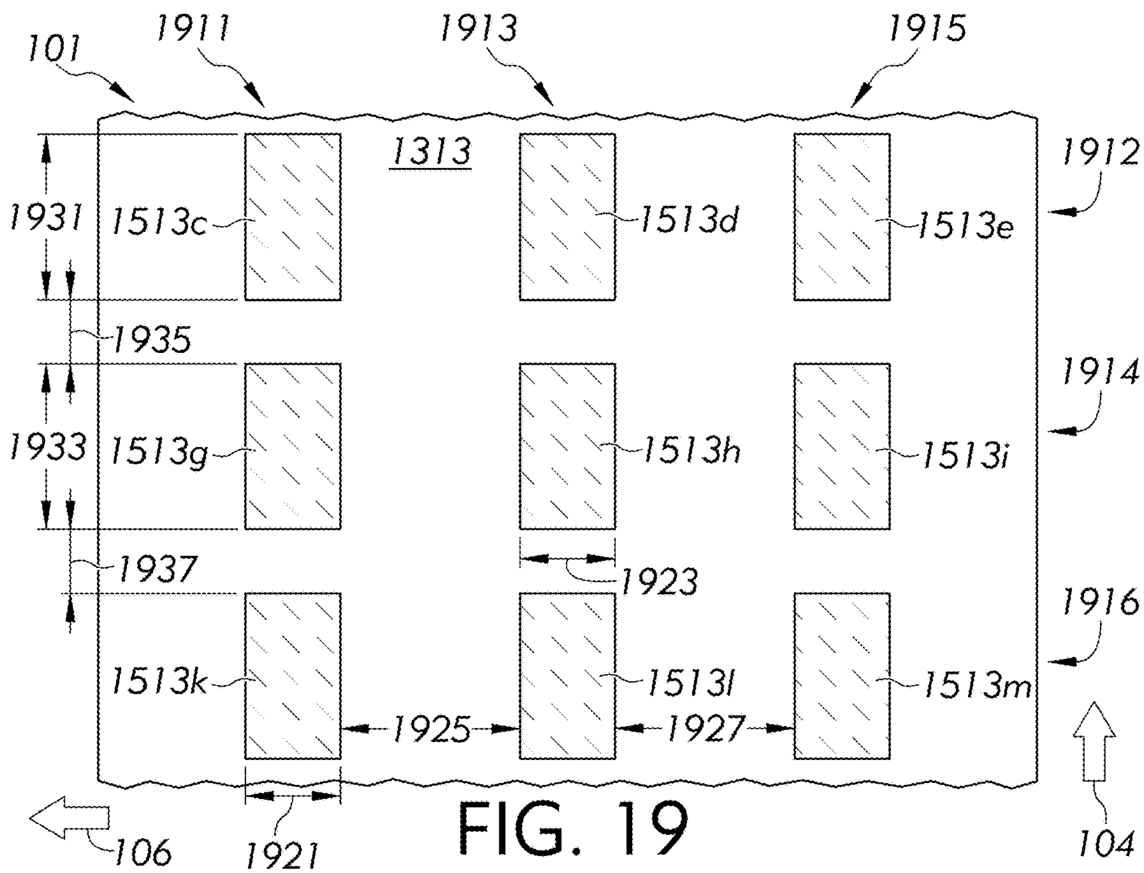

101
1911
1913
1915
1313
1912
1931
1513c
1513d
1513e
1935
1914
1933
1513g
1513h
1513i
1937
1923
1916
1513k
1513l
1513m
1925
1927
104
106
1921

FIG. 19

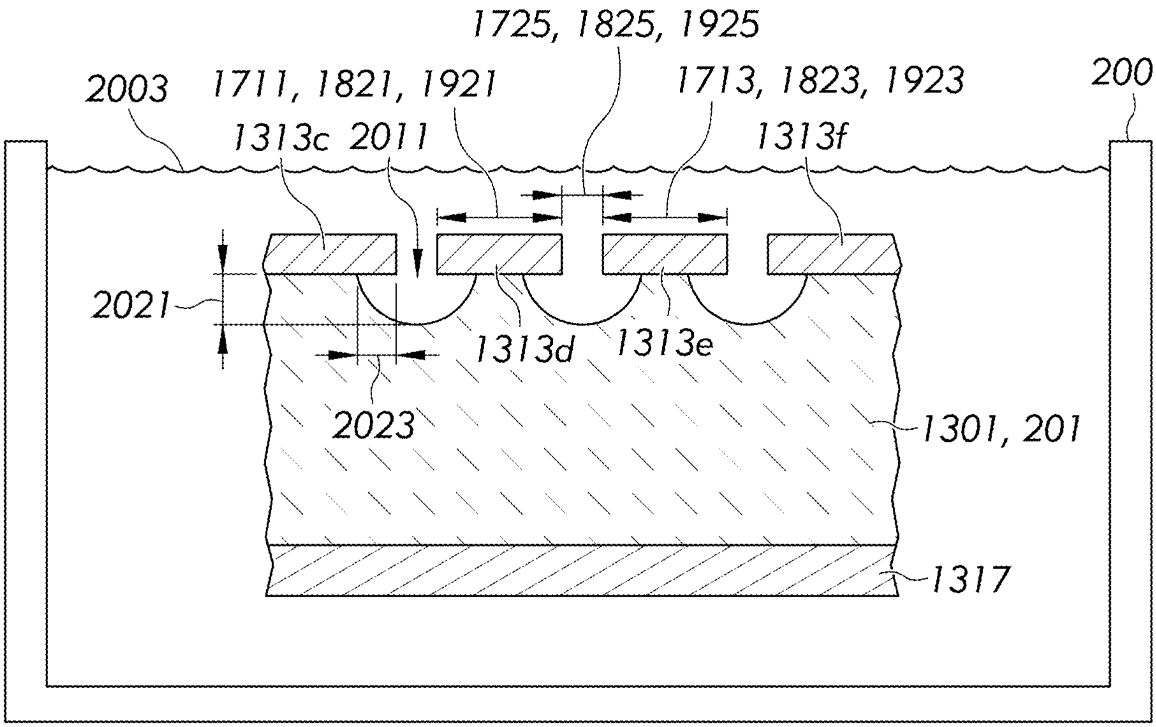

1725, 1825, 1925
2003
1711, 1821, 1921
1713, 1823, 1923
2001
1313c
2011
1313f
2021
1313d
1313e
2023
1301, 201
1317

FIG. 20

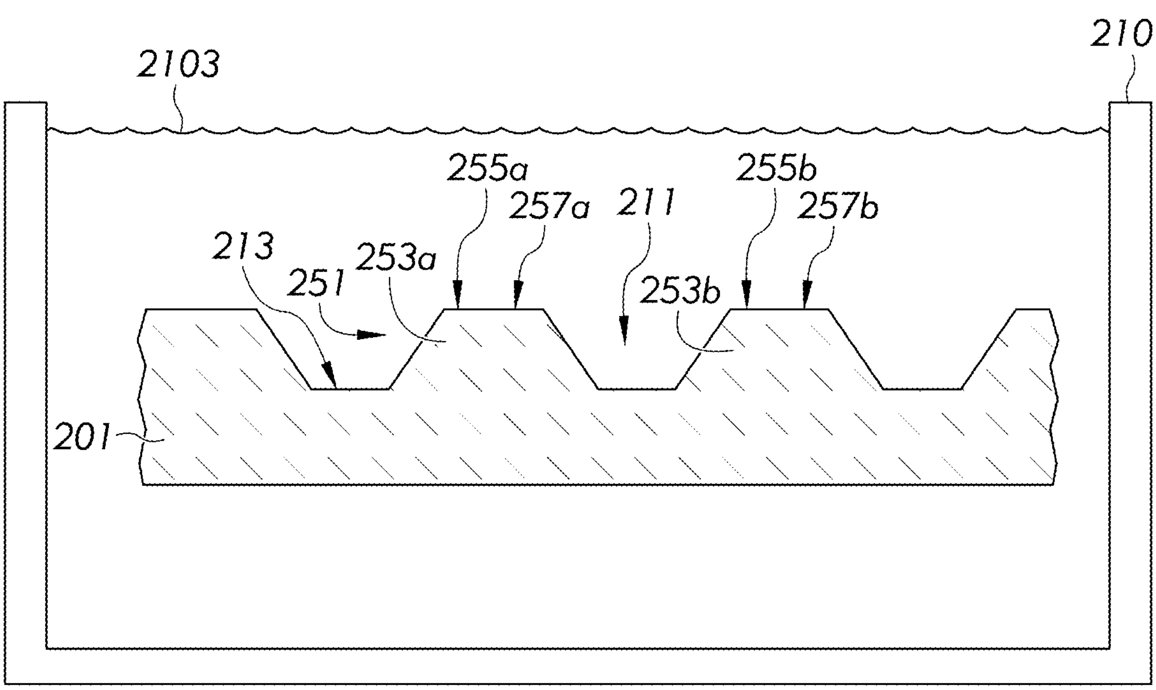

2101
2103
255a
255b
257a
211
257b
213
253a
251
253b
201

FIG. 21

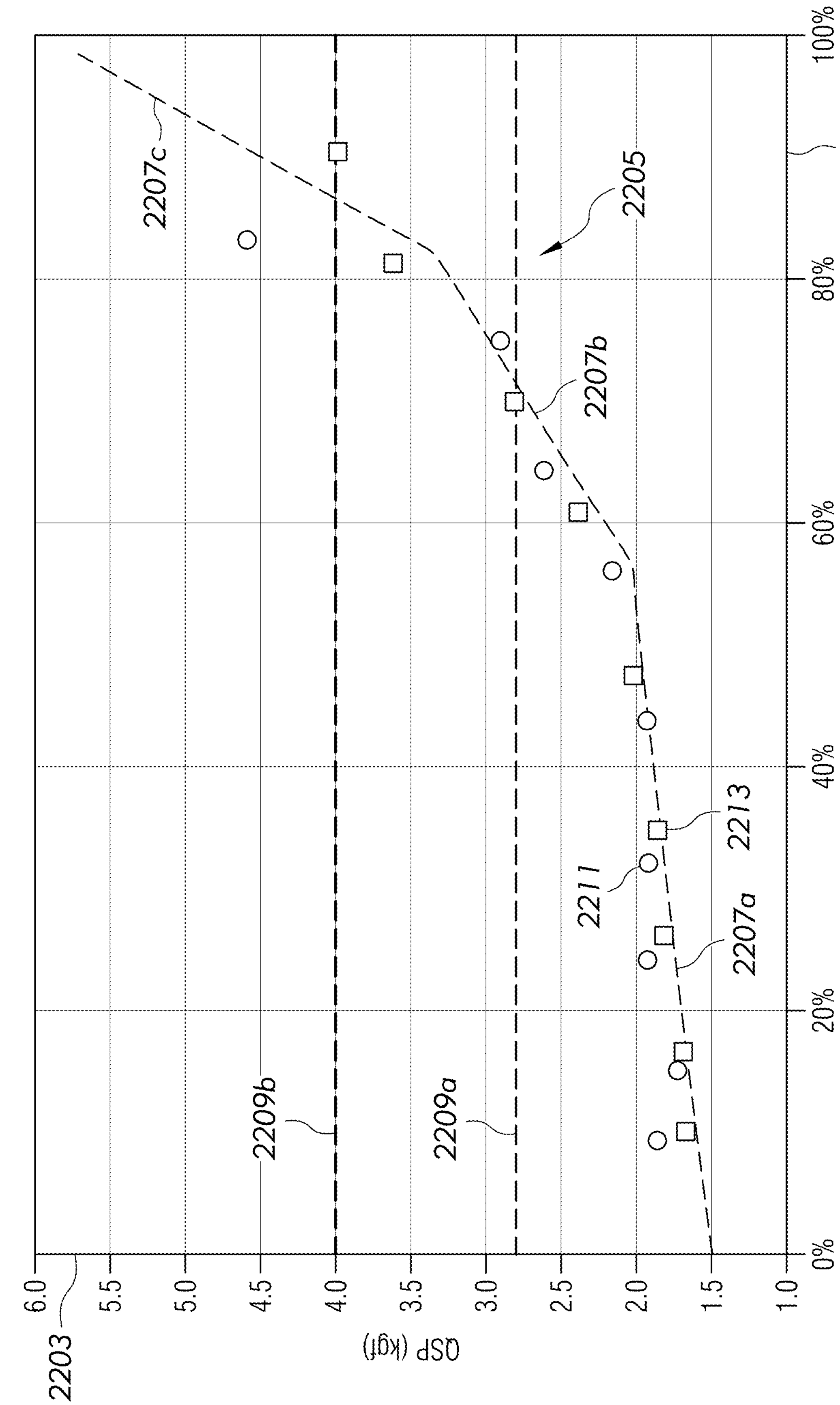
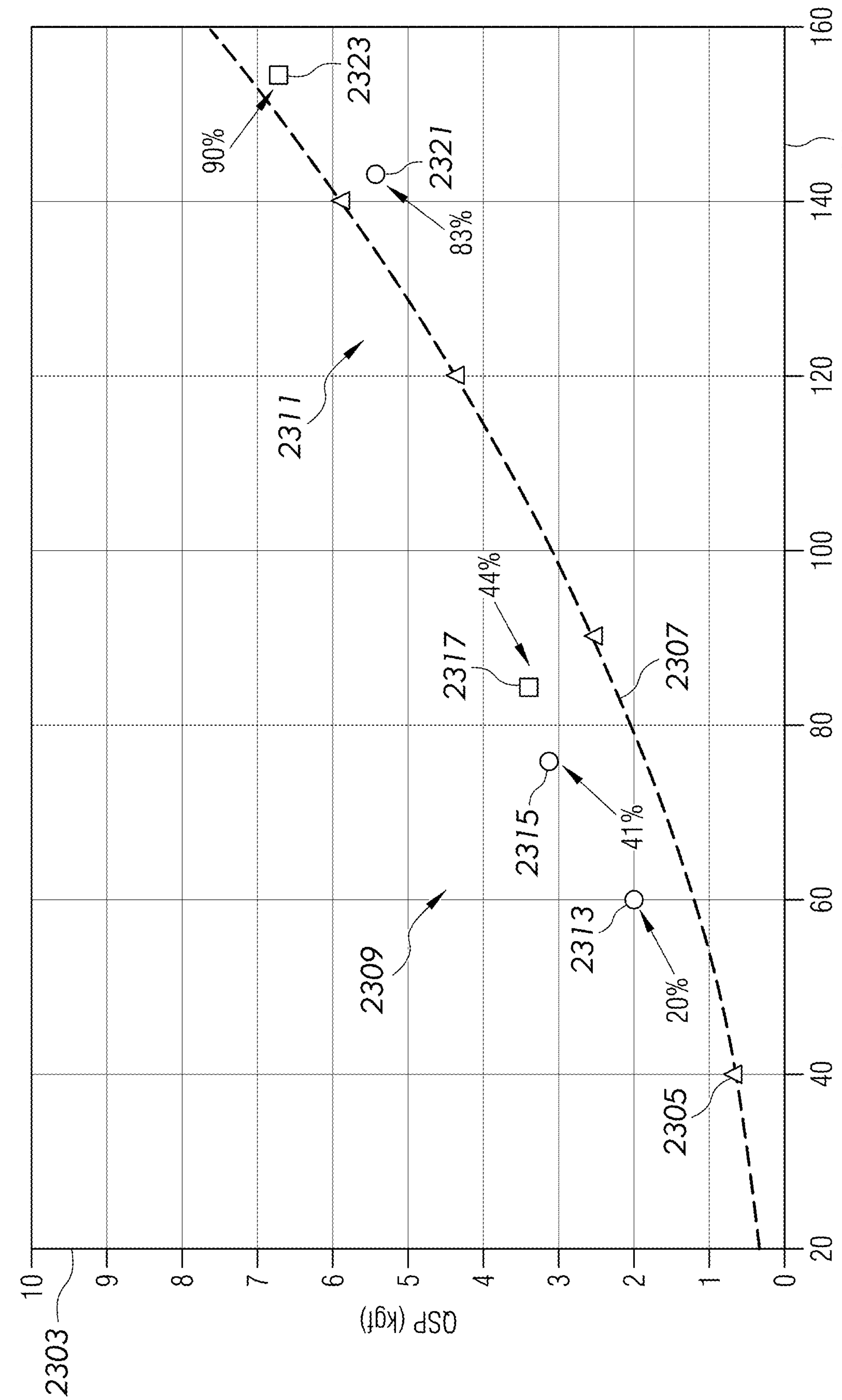

QSP (kgf)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0%
20%
40%
60%
80%
100%
2201
2203
2205
2207a
2207b
2207c
2209a
2209b
2211
2213

FIG. 22



OSP (kgf)
0
1
2
3
4
5
6
7
8
9
10
20
40
60
80
100
120
140
160
2301
2303
2305
2307
2309
2311
2313
2315
2317
2321
2323
20%
41%
44%
83%
90%

FIG. 23

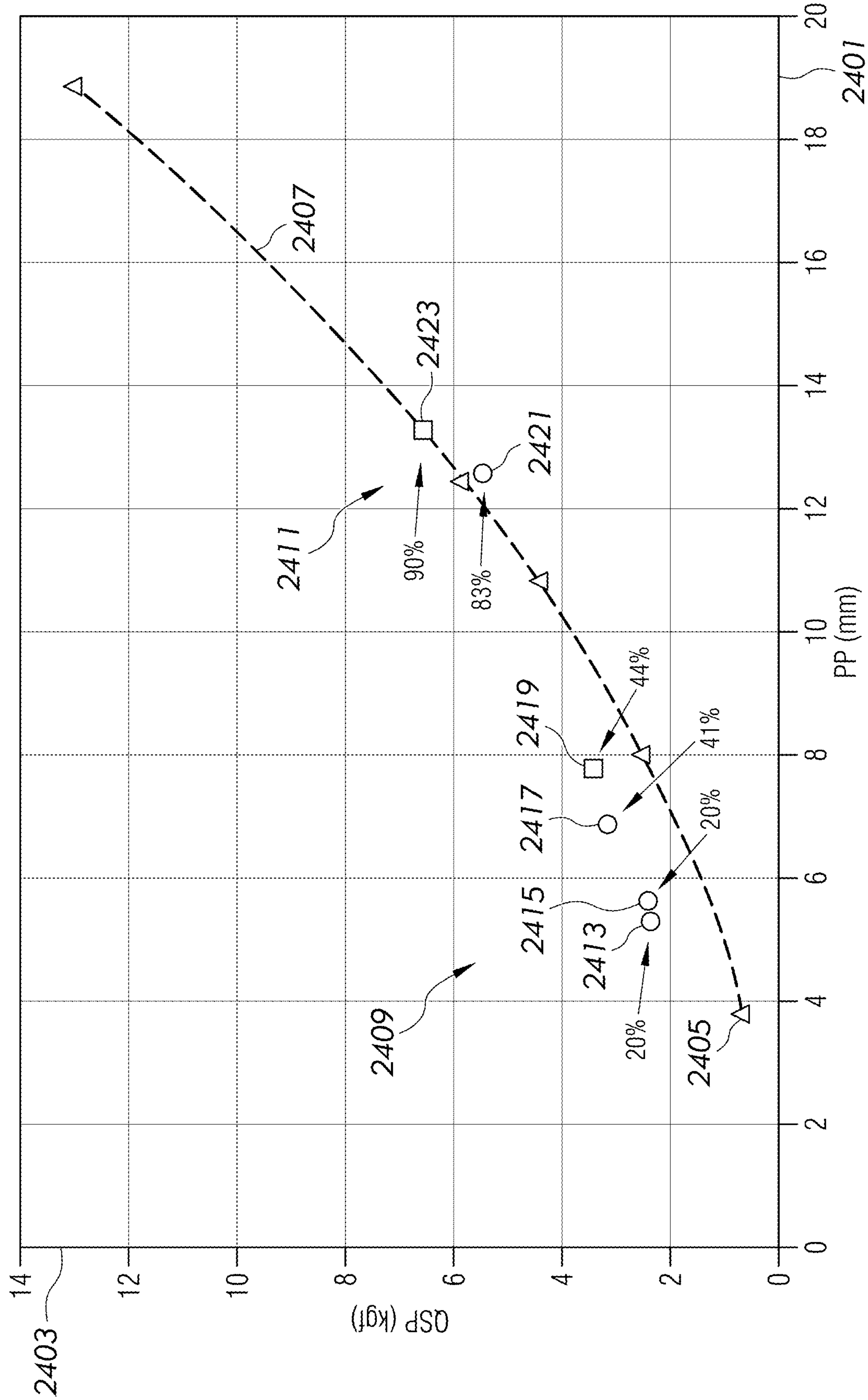
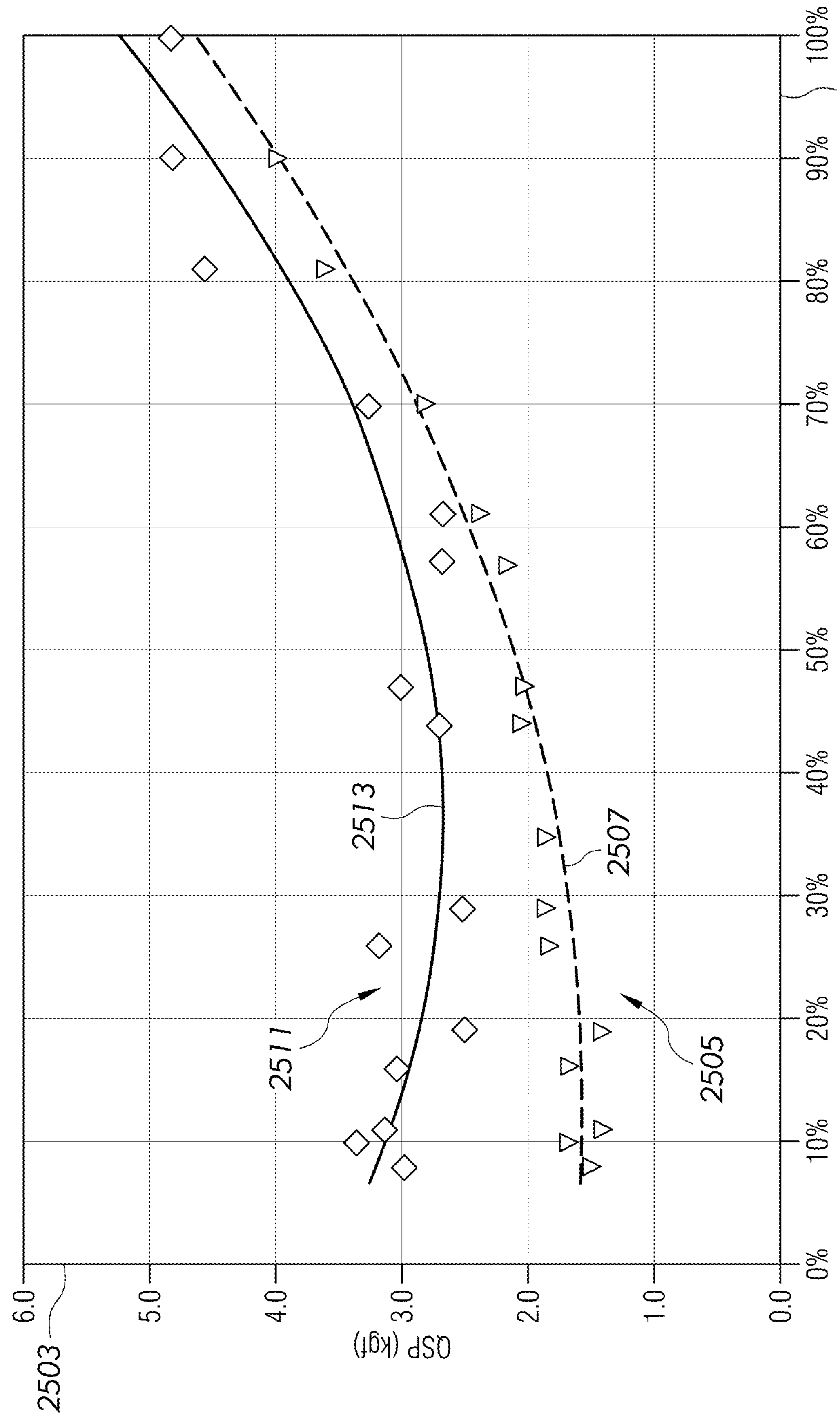

OSP (kgf)
0
2
4
6
8
10
12
14
PP (mm)
0
2
4
6
8
10
12
14
16
18
20
2401
2403
2405
2407
2409
2411
2413
2415
2417
2419
2421
2423
20%
20%
41%
44%
83%
90%

FIG. 24



QSP (kgf)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
2501
2503
2505
2507
2511
2513

FIG. 25

FOLDABLE SUBSTRATES, FOLDABLE ARTICLES, AND METHODS OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Provisional Application Ser. No. 63/552,268, filed on Feb. 12, 2024, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

[0002] The present disclosure relates generally to foldable substrates, foldable articles, and methods of making the same and, more particularly, to foldable substrates comprising a plurality of protrusions, foldable substrates containing the same, and methods of making the same.

BACKGROUND

[0003] Glass-based substrates are commonly used, for example, in display devices, for example, liquid crystal displays (LCDs), electrophoretic displays (EPD), organic light-emitting diode displays (OLEDs), plasma display panels (PDPs), or the like.

[0004] There is a desire to develop foldable versions of displays as well as foldable protective covers to mount on foldable displays. Foldable displays and covers should have good impact and puncture resistance. At the same time, foldable displays and covers should have small minimum bend radii (e.g., about 10 millimeters (mm) or less). However, plastic displays and covers with small minimum bend radii tend to have poor impact and/or puncture resistance. Furthermore, conventional wisdom suggests that ultra-thin glass-based sheets (e.g., about 75 micrometers (μm or microns) or less thick) with small minimum bend radii tend to have poor impact and/or puncture resistance. Furthermore, thicker glass-based sheets (e.g., greater than 125 micrometers) with good impact and/or puncture resistance tend to have relatively large minimum bend radii (e.g., about 30 millimeters or more). Consequently, there is a need to develop foldable apparatus that have low minimum bend radii and good impact and puncture resistance.

SUMMARY

[0005] There are set forth herein foldable apparatus comprising foldable substrates, foldable substrates, and methods of making foldable apparatus and foldable substrates comprising foldable substrates that comprise a first portion, a second portion, and a central portion positioned therebetween. The foldable substrate can comprise glass-based and/or ceramic-based portions, which can provide good dimensional stability, reduced incidence of mechanical instabilities, good impact resistance, and/or good puncture resistance. The portions can comprise one or more compressive stress regions, which can further provide increased impact resistance and/or increased puncture resistance. By providing a foldable substrate comprising a glass-based and/or ceramic-based substrate, the foldable substrate can also provide increased impact resistance and/or puncture resistance while simultaneously facilitating good folding performance. In aspects, the substrate thickness can be sufficiently large (e.g., from about 50 micrometers (microns or μm) to about 2 millimeters) to further enhance impact resistance and puncture resistance. Providing foldable substrates comprising a central portion comprising a central thickness that is less than a substrate thickness (e.g., first thickness of the first portion and/or second thickness of the second portion) (e.g., by about 10 μm or more) can enable a small parallel plate distance (e.g., about 10 millimeters (mm) or less, about 5 mm or less, or about 3 mm or less) based on the reduced thickness in the central portion, which can enable the foldability and/or rollability of the foldable substrate and/or foldable apparatus.

[0006] In aspects, the foldable apparatus and/or foldable substrates can comprise a recess, for example, a first central surface area recessed from a first major surface by a first distance. Providing a recess can form a central thickness that is less than a substrate thickness, which can facilitate folding of the foldable substrate and/or foldable apparatus. Further, providing the recess (e.g., with the plurality of protrusions) on only one side of the foldable substrate can provide a uniform opposite surface that can present a smooth, consistent surface for a user to interact with.

[0007] In aspects, the foldable apparatus and/or foldable substrates can comprise a recess, for example, a first central surface area recessed from a first major surface by a first distance. Providing a recess can provide a central thickness that is less than a substrate thickness, which can facilitate folding of the foldable substrate and/or foldable apparatus. Further, providing the recess (e.g., with the plurality of protrusions) on only one side of the foldable substrate can provide a uniform opposite surface that can present a smooth, consistent surface for a user to interact with.

[0008] The inventors of the present application have unexpectedly determined that providing a plurality of protrusions can improve impact resistance (e.g., as measured in the Quasi-Static Puncture Test) while allowing the foldable substrate and/or foldable substrate to still attain low parallel plate distances. Specifically, as discussed below with reference to FIG. **24**, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness with the same parallel plate distance (e.g., minimum parallel plate distance) (where the parallel plate distance and impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance without negatively impacting foldability (e.g., parallel plate distance). Also, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness equal to a weighted average thickness (defined below) (where the impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance beyond what would be achieved for a substrate with the same weighted average thickness. Being above the calibration curve corresponds to an improvement in impact resistance beyond what would be expected (or obtained) for a monolithic substrate with a minimum parallel plate distance equal to that of the foldable substrate. For example, providing an area ratio from 0.10 to 0.70 (e.g., from 0.20 to 0.60, or from 0.25 to 0.50) can unexpectedly provide improved impact resistance (e.g., as

measured in the Quasi-Static Puncture Test), for example, relative to a reference substrate with the same parallel plate distance or with the same weighted average thickness. Also, providing a plurality of protrusions arranged such that there is not a protrusion of the plurality of protrusions impinged by the midline (e.g., fold plane **109**) can decrease a bend-induced stress on the foldable substrate.

[0009] Providing rounded corners for the cross-sectional shape of a protrusion of the plurality of protrusions can decrease stress concentrations at the corners of the protrusions, which can decrease a maximum bending stress associated with folding to a predetermined parallel plate distance and/or increase a reliability of folding the foldable substrate and/or foldable apparatus. Also, providing a plurality of protrusions (e.g., comprising substantially the substrate thickness) can increase a puncture resistance of the central region (e.g., due to the increased thickness of the plurality of protrusions relative to the first central surface area) while the central region (excluding the plurality of protrusions) can still facilitate folding of the foldable apparatus and/or foldable substrate. In further aspects, providing a plurality of substantially constant local thicknesses (e.g., substantially equal to the central thickness) between corresponding adjacent pairs of protrusions of the plurality of protrusions can simplify manufacturing, for example, enabling the local thickness between an adjacent pair of protrusions to be formed in a single etching step (e.g., with the portions corresponding to the adjacent pair of protrusions being masked).

[0010] Some example aspects of the disclosure are described below with the understanding that any of the features of the various aspects may be used alone or in combination with one another.

[0011] Aspect 1. A foldable substrate comprising:

- **[0012]** a substrate thickness defined between a first major surface and a second major surface opposite the first major surface in a thickness direction;
- **[0013]** a first portion comprising the substrate thickness;
- **[0014]** a second portion comprising the substrate thickness;
- **[0015]** a central portion positioned between the first portion and the second portion, the central portion comprising a first central surface area and a second central surface area opposite the first central surface area, a central thickness defined between the first central surface area and the second central surface area in the thickness direction the central thickness is less than the substrate thickness; and
- **[0016]** a plurality of protrusions extending from the first central surface area by at least 5 micrometers, each protrusion comprising an upper surface within 5 micrometers in the thickness direction from a point corresponding to a maximum height of the corresponding protrusion from the first central surface area;
- **[0017]** a total protrusion area is a sum of an area of the upper surface of each protrusion of the plurality of protrusions, a total central area is an area of the central portion in a plane perpendicular to the thickness direction and impinging the first central surface area,
- **[0018]** wherein the foldable substrate comprises a glass-based material or a ceramic-based material, and an area ratio of the total protrusion area to the total central area is from 0.10 to 0.70.

[0019] Aspect 2. The foldable substrate of aspect 1, wherein the area ratio of the total protrusion area to the total central area is from 0.20 to 0.60.

[0020] Aspect 3. The foldable substrate of any one of aspects 1-2, wherein the area ratio of the total protrusion area to the total central area is from 0.25 to 0.50.

[0021] Aspect 4. The foldable substrate of any one of aspects 1-3, wherein the plurality of protrusions extend from the first central surface area by at least 10 micrometers.

[0022] Aspect 5. The foldable substrate of any one of aspects 1-4, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test from 1 millimeter to 6 millimeters.

[0023] Aspect 6. The foldable substrate of any one of aspects 1-4, wherein the foldable substrate achieves a parallel plate distance in a Parallel Plate Test of 5 millimeters or less.

[0024] Aspect 7. The foldable substrate of any one of aspects 1-4, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test, a reference substrate comprises a monolithic thickness and achieves a reference minimum parallel plate distance in the Parallel Plate Test substantially equal to the minimum parallel plate distance of the foldable substrate, and a puncture resistance of the foldable substrate measured in a Quasi-Static Puncture Test is greater than a reference puncture resistance of the reference substrate measured in the Quasi-Static Puncture Test.

[0025] Aspect 8. The foldable substrate of any one of aspects 1-4, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test and exhibits a puncture resistance measured in a Quasi-Static Puncture Test, the puncture resistance is greater than a predicted puncture resistance for the minimum parallel plate distance based on a calibration curve from a plurality of reference substrates comprising the same material as the foldable substrate and monolithic thicknesses including values of the monolithic thicknesses that achieve corresponding minimum parallel plate distances greater than the minimum parallel plate distance of the foldable substrate and less than the minimum parallel plate distance of the foldable substrate.

[0026] Aspect 9. The foldable substrate of any one of aspects 1-6 or 8 inclusive, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as $TWA=(1-AR)*TC+AR*TP$, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a reference puncture resistance of a reference substrate comprising a uniform thickness equal to the weighted average thickness and the same material as the foldable substrate.

[0027] Aspect 10. The foldable substrate of any one of aspects 1-7, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as $TWA=(1-AR)*TC+AR*TP$, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a predicted puncture resistance for the weighted average thickness based on a calibration curve from a plurality of reference substrates comprising the same material as the foldable substrate and monolithic thicknesses including values of the monolithic thicknesses greater than the weighted average thickness and less than the weighted average thickness.

[0028] Aspect 11. The foldable substrate of any one of aspect 1-8, wherein a combined thickness between the second central surface area of the central portion and the upper surface of the protrusion is less than or equal to the substrate thickness.

[0029] Aspect 12. The foldable substrate of any one of aspect 1-8, wherein the first major surface extends along a first plane, a first distance is defined between the first plane and the first central surface area in the thickness direction, a protrusion height defined between the first central surface area and the upper surface of a protrusion of the plurality of protrusions in the thickness direction, and the first distance is greater than or equal to the protrusion height.

[0030] Aspect 13. The foldable substrate of aspect 12, wherein a ratio of the protrusion height to the first distance is from 0.30 to 1.0.

[0031] Aspect 14. The foldable substrate of aspect 12, wherein the first distance is substantially equal to the protrusion height.

[0032] Aspect 15. The foldable substrate of any one of aspect 9-14, wherein a width of the upper surface of a protrusion of the plurality of protrusions in a direction between the first portion and the second portion is from 20 micrometers to 1 millimeter.

[0033] Aspect 16. The foldable substrate of aspect 15, wherein the protrusion width is from 80 micrometers to 310 micrometers.

[0034] Aspect 17. The foldable substrate of any one of aspect 1-16, wherein the plurality of protrusions are aligned in a row extending in a first direction between the first portion and the second portion.

[0035] Aspect 18. The foldable substrate of aspect 17, wherein the foldable substrate comprises a substrate width measured in a width direction perpendicular to the thickness direction and the first direction, a protrusion of the plurality of protrusions extends for a distance in the width direction that is from 50% of the substrate width to 100% of the substrate width.

[0036] Aspect 19. The foldable substrate of aspect 17, wherein the plurality of protrusions are arranged in a two-dimensional array including the row extending between the first portion and the second portion, and at least three protrusions of the plurality of protrusions in a column of a plurality of columns extending perpendicular to the row.

[0037] Aspect 20. The foldable substrate of aspect 19, wherein protrusions of the plurality of protrusions in a first column of the plurality of columns is aligned with corresponding protrusions of a second column of the plurality of columns, where the first column is adjacent to the second column.

[0038] Aspect 21. The foldable substrate of aspect 19, wherein protrusions of the plurality of protrusions in a first column of the plurality of columns is offset from corresponding protrusions of a second column of the plurality of columns, where the first column is adjacent to the second column.

[0039] Aspect 22. The foldable substrate of any one of aspects 16-21, wherein a gap width between adjacent protrusions in the row in the first direction is from 150 micrometers to 1 millimeter.

[0040] Aspect 23. The foldable substrate of aspect 22, wherein the gap width is from 200 micrometers to 500 micrometers.

[0041] Aspect 24. The foldable substrate of any one of aspects 1-23, wherein the second major surface comprises the second central surface area.

[0042] Aspect 25. The foldable substrate of any one of aspects 1-23, wherein the second major surface is flush with the second central surface area.

[0043] Aspect 26. The foldable substrate of any one of aspects 1-25, further comprising:

[0044] a first compressive stress region extending to a first depth of compression from the first major surface in the first portion;

[0045] a second compressive stress region extending to a second depth of compression from the second major surface in the first portion;

[0046] a third compressive stress region extending to a third depth of compression from the first major surface in the second portion; and

[0047] a fourth compressive stress region extending to a fourth depth of compression from the second major surface in the second portion.

[0048] Aspect 27. The foldable substrate of aspect 26, further comprising:

[0049] a first central compressive stress region extending to a first central depth of compression from the first central surface area; and

[0050] a second central compressive stress region extending to a second central depth of compression from the second central surface area.

[0051] Aspect 28. The foldable substrate of any one of aspects 26-27, wherein the first compressive stress region comprises a first maximum compressive stress of about 400 MegaPascals or more, the second compressive stress region comprises a second maximum compressive stress, the third compressive stress region comprises a third maximum compressive stress of about 400 MegaPascals or more, and the fourth compressive stress region comprises a fourth maximum compressive stress.

[0052] Aspect 29. The foldable substrate of aspect 28, wherein the second maximum compressive stress is about 400 MegaPascals or more, and the fourth maximum compressive stress is about 400 MegaPascals or more.

[0053] Aspect 30. The foldable substrate of any one of aspects 1-29, wherein the substrate thickness is in a range from about 50 micrometers to about 5 millimeters.

[0054] Aspect 31. The foldable substrate of any one of aspects 1-29, wherein the substrate thickness is in a range from about 100 micrometers to about 200 micrometers.

[0055] Aspect 32. The foldable substrate of any one of aspects 1-31, wherein the central thickness in a range from about 25 micrometers to about 120 micrometers.

[0056] Aspect 33. The foldable substrate of any one of aspects 1-31, wherein the central thickness is in a range from about 25 micrometers to about 80 micrometers.

[0057] Aspect 34. The foldable substrate of any one of aspects 1-33, wherein the foldable substrate comprises a glass-based substrate.

[0058] Aspect 35. The foldable substrate of any one of aspects 1-33, wherein the foldable substrate comprises a ceramic-based substrate.

[0059] Aspect 36. A foldable apparatus comprising:

[0060] the foldable substrate of any one of aspects 1-35; and

[0061] a polymer-based portion positioned at least between an adjacent pair of protrusions of the plurality of protrusions,

[0062] wherein a magnitude of a difference between an index of refraction of the foldable substrate and an index of refraction of the polymer-based portion is about 0.1 or less.

[0063] Aspect 37. A consumer electronic product, comprising:

[0064] a housing comprising a front surface, a back surface, and a side surface;

[0065] electrical components at least partially within the housing, the electrical components comprising a controller, a memory, and a display, the display at or adjacent the front surface of the housing; and

[0066] a cover substrate disposed over the display,

[0067] wherein at least one of a portion of the housing or the cover substrate comprises the foldable substrate of any one of aspects 1-35.

[0068] Aspect 38. A method of making a foldable substrate comprising:

[0069] disposing a patterned mask on a central portion of an initial major surface of an initial substrate, the patterned mask comprising a plurality of separate sections; and

[0070] etching the initial major surface of the initial substrate to form a central portion of the foldable substrate with a plurality of protrusions extending from a first central surface area by at least 5 micrometers, and the plurality of protrusions corresponding to the plurality of separate sections of the patterned mask on central portion of the initial major surface,

[0071] wherein each protrusion of the plurality of protrusions comprising an upper surface within 5 micrometers in the thickness direction from a point corresponding to a maximum height of the corresponding protrusion from the first central surface area,

[0072] a total protrusion area is a sum of sum of an area of the upper surface of each protrusion of the plurality of protrusions, a total central area is an area of the central portion in the plane perpendicular to the thickness direction and impinging the first central surface area, the foldable substrate comprises a glass-based material or a ceramic-based material, and an area ratio of the total protrusion area to the total central area is from 0.10 to 0.70.

[0073] Aspect 39. The method of aspect 38, wherein the area ratio of the total protrusion area to the total central area is from 0.20 to 0.60.

[0074] Aspect 40. The method of any one of aspects 38-39, wherein the area ratio of the total protrusion area to the total central area is from 0.25 to 0.50.

[0075] Aspect 41. The method of any one of aspects 38-40, wherein the plurality of protrusions extend from the first central surface area by at least 10 micrometers.

[0076] Aspect 42. The method of any one of aspects 38-41, wherein the disposing the patterned mask comprises ink-jet printing the patterned mask.

[0077] Aspect 43. The method of any one of aspects 38-42, wherein, before etching the initial major surface, the method comprises disposing a first mask over a first portion of the initial major surface and a second mask of a second portion of the initial major surface, the central portion positioned between the first portion and the second portion.

[0078] Aspect 44. The method of any one of aspects 38-42, wherein, before etching the initial major surface, the method comprises disposing a third mask over an opposing major surface of the initial substrate opposite the initial major surface.

[0079] Aspect 45. The method of any one of aspects 38-44, a section of the plurality of sections comprises a width from 50 micrometers to 1 millimeter.

[0080] Aspect 46. The method of any one of aspects 38-45, wherein the plurality of sections are aligned in a row extending in a first direction.

[0081] Aspect 47. The method of aspect 46, wherein the plurality of sections are arranged in a two-dimensional array including the row, and at least three sections of the plurality of sections are in a column of a plurality of columns extending perpendicular to the row.

[0082] Aspect 48. The method substrate of aspect 47, wherein sections of the plurality of sections in a first column of the plurality of columns is aligned with corresponding sections of a second column of the plurality of columns, where the first column is adjacent to the second column.

[0083] Aspect 49. The method of aspect 47, wherein sections of the plurality of sections in a first column of the plurality of columns is offset from corresponding section of a second column of the plurality of columns, where the first column is adjacent to the second column.

[0084] Aspect 50. The method of any one of aspects 46-49, wherein a gap between adjacent sections in the row in the first direction is from 150 micrometers to 1 millimeter.

[0085] Aspect 51. The method of any one of aspects 38-50, wherein the foldable substrate comprises:

[0086] a substrate thickness defined between the first major surface and a second major surface opposite the first major surface in a thickness direction;

[0087] a first portion comprising the substrate thickness;

[0088] a second portion comprising the substrate thickness; and

[0089] a central portion positioned between the first portion and the second portion, the central portion comprising the first central surface area and a second central surface area opposite the first central surface area, a central thickness defined between the first central surface area and the second central surface area in the thickness direction the central thickness is less than the substrate thickness.

[0090] Aspect 52. The method of aspect 51, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test from 1 millimeter to 6 millimeters.

[0091] Aspect 53. The method of aspect 51, wherein the foldable substrate achieves a parallel plate distance in a Parallel Plate Test of 5 millimeters or less.

[0092] Aspect 54. The method of aspect 51, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test, a reference substrate comprises a monolithic thickness and achieves a reference minimum parallel plate distance in the Parallel Plate Test substantially equal to the minimum parallel plate distance of the foldable substrate, and a puncture resistance of the foldable substrate measured in a Quasi-Static Puncture Test is greater than a reference puncture resistance of the reference substrate measured in the Quasi-Static Puncture Test.

[0093] Aspect 55. The method of aspect 51, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test and exhibits a puncture resistance measured in a Quasi-Static Puncture Test, the puncture resistance is greater than a predicted puncture resistance for the minimum parallel plate distance based on a calibration curve from a plurality of reference substrates comprising the same material as the foldable substrate and monolithic thicknesses including values of the monolithic thicknesses that achieve corresponding minimum parallel plate distances greater than the minimum parallel plate distance of the foldable substrate and less than the minimum parallel plate distance of the foldable substrate.

[0094] Aspect 56. The method of aspects 51-53 or 55 inclusive, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as TWA=(1−AR)*TC+AR*TP, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a reference puncture resistance of a reference substrate comprising a uniform thickness equal to the weighted average thickness and the same material as the foldable substrate.

[0095] Aspect 57. The method of any one of aspects 51-54, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as TWA=(1−AR)*TC+AR*TP, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a predicted puncture resistance for the weighted average thickness based on a calibration curve from a plurality of reference substrates comprising the same material as the foldable substrate and monolithic thicknesses including values of the monolithic thicknesses greater than the weighted average thickness and less than the weighted average thickness.

[0096] Aspect 58. The method of any one of aspects 51-57, wherein a combined thickness between the second central surface area of the upper surface of a protrusion of the plurality of protrusions is less than or equal to the substrate thickness.

[0097] Aspect 59. The method of any one of aspects 51-57, wherein the first major surface extends along a first plane, a first distance is defined between the first plane and the first central surface area in the thickness direction, a protrusion height defined the first central surface area and the upper surface of a protrusion of the plurality of protrusions in the thickness direction, and the first distance is greater than or equal to the protrusion height.

[0098] Aspect 60. The method of aspect 59, wherein a ratio of the protrusion height to the first distance is from 0.30 to 1.0.

[0099] Aspect 61. The method of aspect 59, wherein the first distance is substantially equal to the protrusion height.

[0100] Aspect 62. The method of any one of aspects 38-61, further comprising chemically strengthening the foldable substrate by simultaneously exposing the first major surface, the first central surface area, and the plurality of protrusions to a molten salt solution,

[0101] wherein the chemically strengthening forms:

[0102] a first compressive stress region extending to a first depth of compression from the first major surface in the first portion;

[0103] a second compressive stress region extending to a second depth of compression from the first major surface in the second portion; and

[0104] a first central compressive stress region extending to a first central depth of compression from the first central surface area.

[0105] Aspect 63. The method of aspect 62, wherein the first compressive stress region comprises a first maximum compressive stress of about 400

[0106] MegaPascals or more, and the second compressive stress region comprises a second maximum compressive stress of 400 MegaPascals or more.

[0107] Aspect 64. The method of any one of aspects 51-63, wherein the substrate thickness is in a range from about 50 micrometers to about 5 millimeters.

[0108] Aspect 65. The method of any one of aspects 51-63, wherein the substrate thickness is in a range from about 100 micrometers to about 200 micrometers.

[0109] Aspect 66. The method of any one of aspects 51-65, wherein the central thickness in a range from about 25 micrometers to about 120 micrometers.

[0110] Aspect 67. The method of any one of aspects 51-65, wherein the central thickness is in a range from about 25 micrometers to about 60 micrometers.

[0111] Aspect 68. The method of any one of aspects 38-67, wherein the foldable substrate comprises a glass-based substrate.

[0112] Aspect 69. The method of any one of aspects 38-67, wherein the foldable substrate comprises a ceramic-based substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0113] The above and other features and advantages of aspects of the present disclosure are better understood when the following detailed description is read with reference to the accompanying drawings, in which:

[0114] FIG. **1** is a schematic view of an example foldable apparatus in a flat configuration according to aspects, wherein a schematic view of the folded configuration may appear as shown in FIG. **7**;

[0115] FIG. **2** is a cross-sectional view of the foldable apparatus along line **2-2** of FIG. **1** comprising a foldable substrate according to aspects;

[0116] FIG. **3** is an alternative cross-sectional view of a foldable apparatus along line **2-2** of FIG. **1** comprising a foldable substrate according to aspects;

[0117] FIG. **4** is a cross-sectional view of the foldable substrate along line **4-4** of FIG. **2**;

[0118] FIG. **5** is an alternative cross-sectional view of the foldable substrate with aligned rows of protrusions;

[0119] FIG. **6** is an alternative cross-sectional view of the foldable substrate with offset rows of protrusions;

[0120] FIG. **7** is a schematic view of example foldable apparatus of aspects of the disclosure in a folded configuration wherein a schematic view of the flat configuration may appear as shown in FIG. **1**;

[0121] FIG. **8** is a schematic plan view of an example consumer electronic device according to aspects;

[0122] FIG. **9** is a schematic perspective view of the example consumer electronic device of FIG. **8**;

[0123] FIG. **10** is a schematic perspective view of a foldable consumer electronic product;

[0124] FIG. **11** schematically illustrates a test apparatus for performing the Pen Drop Test and/or the Quasi-Static Puncture Test;

[0125] FIG. **12** schematically illustrate a flow chart for methods of making a foldable substrate and/or foldable apparatus;

[0126] FIG. **13** schematically illustrates a step in methods comprising disposing a mask on an initial first major surface of an initial substrate;

[0127] FIG. **14** schematically illustrates a step in methods comprising disposing a patterned mask on an initial first major surface, for example, by ink-jet deposition;

[0128] FIG. **15** schematically illustrates a step in methods comprising forming a patterned mask on the initial first major surface, for example, using a laser;

[0129] FIG. **16** schematically illustrates a patterned mask in accordance with methods of the present disclosure;

[0130] FIG. **17** schematically illustrates the patterned mask in view **17** of FIG. **16**;

[0131] FIG. **18** schematically illustrates another patterned mask comprising aligned rows of protrusions;

[0132] FIG. **19** schematically illustrates another patterned mask comprising offset rows of protrusions;

[0133] FIG. **20** schematically illustrates a step in methods comprising etching the initial first major surface;

[0134] FIG. **21** schematically illustrates a step in methods comprising chemically strengthening the foldable substrate;

[0135] FIG. **22** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis (i.e., y-axis) as a function of an area ratio in percent (%) on the horizontal axis (i.e., x-axis);

[0136] FIG. **23** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis (i.e., y-axis) as a function of thickness of the monolithic reference substrates in micrometers (μm) on the horizontal axis (i.e., x-axis) with samples having a plurality of protrusions plotted based on a corresponding minimum parallel plate distance of a monolithic reference sample;

[0137] FIG. **24** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis (i.e., y-axis) as a function of parallel plate distance in millimeters (mm) on the horizontal axis (i.e., x-axis); and

[0138] FIG. **25** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis (i.e., y-axis) as a function of area ratio in percent (%) on the horizontal axis (i.e., x-axis).

[0139] Throughout the disclosure, the drawings are used to emphasize certain aspects. As such, it should not be assumed that the relative size of different regions, portions, and substrates shown in the drawings are proportional to its actual relative size, unless explicitly indicated otherwise.

DETAILED DESCRIPTION

[0140] Aspects will now be described more fully hereinafter with reference to the accompanying drawings in which example aspects are shown. Whenever possible, the same reference numerals are used throughout the drawings to refer to the same or like parts.

[0141] FIGS. **1-7** illustrate views of foldable apparatus **101** and **301** comprising a foldable substrate **201** having a plurality of protrusions **251** and **351** in accordance with aspects of the disclosure. Unless otherwise noted, a discussion of features of aspects of one foldable apparatus can apply equally to corresponding features of any aspect of the disclosure. For example, identical part numbers throughout the disclosure can indicate that, in some aspects, the identified features are identical to one another and that the discussion of the identified feature of one aspect, unless otherwise noted, can apply equally to the identified feature of any of the other aspects of the disclosure.

[0142] FIGS. **2-6** schematically illustrate example aspects of foldable apparatus **101** and **301** comprising the foldable substrate **201** in accordance with aspects of the disclosure in an unfolded (e.g., flat) configuration while FIG. **7** illustrates an example aspect of a foldable apparatus **301** comprising the foldable substrate **201** in accordance with aspects of the disclosure in a folded configuration. The foldable apparatus **101** and **301** and the foldable substrate **201** comprise a first portion **221** and a second portion **231** with a central portion **281** positioned therebetween. Although not shown in FIGS. **4-6**, it is to be understood that the central portion **281** can be attached to a first portion **221** and/or second portion **231** similar to or identical to the corresponding portions shown in FIGS. **2-3**. Although not shown, it is to be understood that the foldable substrate can be combined with one or more polymer-based portions, adhesive layers, coatings, and/or display devices as the foldable apparatus.

[0143] Throughout the disclosure, with reference to FIG. **1**, the width **103** of the foldable apparatus **101** and/or **301** is considered the dimension of the foldable apparatus taken between opposed edges of the foldable apparatus in a direction **104** of a fold axis **102** of the foldable apparatus, wherein the direction **104** also comprises the direction of the width **103**. Furthermore, throughout the disclosure, the length **105** of the foldable apparatus **101** and/or **301** is considered the dimension of the foldable apparatus **101** and/or **301** taken between opposed edges of the foldable apparatus **101** and/or **301** in a direction **106** perpendicular to the fold axis **102** of the foldable apparatus **101** and/or **301**. It is to be understood that the direction **104** of the width **103** and/or the direction **106** of the length **105** can correspond to corresponding directions in the foldable substrate **201**. In aspects, as shown in FIGS. **1-3**, the foldable apparatus of any aspect of the disclosure can comprise a fold plane **109** that includes the fold axis **102** when the foldable apparatus is in the flat configuration (e.g., see FIGS. **2-3**). In further aspects, as shown in FIGS. **2-3**, the fold plane **109** can extend along the fold axis **102** and in a thickness direction **202** of a substrate thickness **209** when the foldable apparatus is in the flat configuration (e.g., see FIGS. **2-3**). The fold plane **109** may comprise a central axis **107** of the foldable apparatus. In aspects, the foldable apparatus can be folded in a direction **111** (see FIG. **1**) about the fold axis **102** extending in the direction **104** of the width **103** to form a folded configuration (e.g., see FIG. **7** corresponding to folded configurations of the flat configurations shown in FIG. **3**, respectively). As shown, the foldable apparatus and/or the foldable substrate may include a single fold axis to allow the foldable apparatus and/or the foldable substrate to comprise a bifold wherein, for example, the foldable apparatus and/or the foldable substrate may be folded in half. In further aspects, the foldable apparatus and/or the foldable substrate may include two or more fold axes with each fold axis including a corresponding central portion similar or identical to the central portion **281** discussed herein. For example, providing two fold axes can allow the foldable apparatus and/or the foldable substrate to comprise a trifold wherein, for example, the foldable apparatus and/or the foldable substrate may be folded with the first portion **221**, the second portion **231**, and a third portion similar or identical to the first portion or second portion with the central portion **281** and another central portion similar to or identical to the central portion positioned between the first portion and the second portion and between the second portion and the third portion, respectively.

[0144] The foldable substrate **201** can comprise a glass-based substrate and/or a ceramic-based substrate having a pencil hardness of 8H or more, for example, 9H or more. As used herein, pencil hardness is measured using ASTM D 3363-20 with standard lead graded pencils. Providing a glass-based foldable substrate and/or a ceramic-based foldable substrate can enhance puncture resistance and/or impact resistance.

[0145] In aspects, the foldable substrate **201** can comprise a glass-based substrate. As used herein, "glass-based" includes both glasses and glass-ceramics, wherein glass-ceramics have one or more crystalline phases and an amorphous, residual glass phase. A glass-based material (e.g., glass-based substrate) may comprise an amorphous material (e.g., glass) and optionally one or more crystalline materials (e.g., ceramic). Amorphous materials and glass-based materials may be strengthened. As used herein, the term "strengthened" may refer to a material that has been chemically strengthened, for example, through ion exchange of larger ions for smaller ions in the surface of the substrate, as discussed below. However, other strengthening methods, for example, thermal tempering, or utilizing a mismatch of the coefficient of thermal expansion between portions of the substrate to create compressive stress and central tension regions, may be utilized to form strengthened substrates. Exemplary glass-based materials, which may be free of lithia or not, comprise soda lime glass, alkali aluminosilicate glass, alkali-containing borosilicate glass, alkali-containing aluminoborosilicate glass, alkali-containing phosphosilicate glass, and alkali-containing aluminophosphosilicate glass. In aspects, glass-based material can comprise an alkali-containing glass or an alkali-free glass, either of which may be free of lithia or not. In aspects, the glass material can be alkali-free and/or comprise a low content of alkali metals (e.g., R_2O of 10 mol % or less, wherein R_2O comprises Li_2O Na_2O, K_2O, or the more expansive list provided below). In one or more aspects, a glass-based material may comprise, in mole percent (mol %): SiO_2 in a range from 40 mol % to 80 mol %, Al_2O_3 in a range from 5 mol % to 30 mol %, B_2O_3 in a range from 0 mol % to 10 mol %, ZrO_2 in a range from 0 mol % to 5 mol %, P_2O_5 in a range from 0 mol % to 15 mol %, TiO_2 in a range from 0 mol % to 2 mol %, R_2O in a range from 0 mol % to 20 mol %, and RO in a range from 0 mol % to 15 mol %. As used herein, R_2O can refer to an alkali-metal oxide, for example, Li_2O, Na_2O, K_2O, Rb_2O, and Cs_2O. As used herein, RO can refer to MgO, CaO, SrO, BaO, and ZnO. In aspects, a glass-based substrate may optionally further comprise in a range from 0 mol % to 2 mol % of each of Na_2SO_4, NaCl, NaF, NaBr, K_2SO_4, KCl, KF, KBr, As_2O_3, Sb_2O_3, SnO_2, Fe_2O_3, MnO, MnO_2, MnO_3, Mn_2O_3, Mn_3O_4, Mn_2O_7. "Glass-ceramics" include materials produced through controlled crystallization of glass. In aspects, glass-ceramics have from 1% to 99% (e.g., from 10% to 90%, or from 20% to 75%) crystallinity. Examples of suitable glass-ceramics may include Li_2O—Al_2O_3—SiO_2 system (i.e., LAS-System) glass-ceramics, MgO—Al_2O_3—SiO_2 system (i.e., MAS-System) glass-ceramics, ZnO×Al_2O_3×nSiO_2 (i.e., ZAS system), and/or glass-ceramics that include a predominant crystal phase including β-quartz solid solution, β-spodumene, cordierite, petalite, and/or lithium disilicate. The glass-ceramic substrates may be strengthened using the chemical strengthening processes. In one or more aspects, MAS-System glass-ceramic substrates may be strengthened in Li_2SO_4 molten salt, whereby an exchange of $2Li^+$ for Mg^{2+} can occur.

[0146] In aspects, the foldable substrate **201** can comprise a ceramic-based substrate. As used herein, "ceramic-based" includes both ceramics and glass-ceramics, wherein glass-ceramics have one or more crystalline phases and an amorphous, residual glass phase. Ceramic-based materials may be strengthened (e.g., chemically strengthened). In aspects, a ceramic-based material can be formed by heating a glass-based material to form ceramic (e.g., crystalline) portions. In further aspects, ceramic-based materials may comprise one or more nucleating agents that can facilitate the formation of crystalline phase(s). In aspects, ceramic-based materials can comprise one or more oxides, nitrides, oxynitrides, carbides, borides, and/or silicides. Example aspects of ceramic oxides include zirconia (ZrO_2), zircon ($ZrSiO_4$), an alkali-metal oxide (e.g., sodium oxide (Na_2O)), an alkali earth metal oxide (e.g., magnesium oxide (MgO)), titania (TiO_2), hafnium oxide (Hf_2O), yttrium oxide (Y_2O_3), iron oxides, beryllium oxides, vanadium oxide (VO_2), fused quartz, mullite (a mineral comprising a combination of aluminum oxide and silicon dioxide), and spinel ($MgAl_2O_4$). Example aspects of ceramic nitrides include silicon nitride (Si_3N_4), aluminum nitride (AlN), gallium nitride (GaN), beryllium nitride (Be_3N_2), boron nitride (BN), tungsten nitride (WN), vanadium nitride, alkali earth metal nitrides (e.g., magnesium nitride (Mg_3N_2)), nickel nitride, and tantalum nitride. Example aspects of oxynitride ceramics include silicon oxynitride, aluminum oxynitride, and a SiAlON (a combination of alumina and silicon nitride and can have a chemical formula, for example, $Si_{12-m-n}Al_{m+n}O_nN_{16-n}$, $Si_{6-n}Al_nO_nN_{8-n}$, or $Si_{2-n}Al_nO_{1+n}N_{2-n}$, where m, n, and the resulting subscripts are all non-negative integers). Example aspects of carbides and carbon-containing ceramics include silicon carbide (SiC), tungsten carbide (WC), an iron carbide, boron carbide (B_4C), alkali-metal carbides (e.g., lithium carbide (Li_4C_3)), alkali earth metal carbides (e.g., magnesium carbide (Mg_2C_3)), and graphite. Example aspects of borides include chromium boride (CrB_2), molybdenum boride (Mo_2B_5), tungsten boride (W_2B_5), iron boride, titanium boride, zirconium boride (ZrB_2), hafnium boride (HfB_2), vanadium boride (VB_2), Niobium boride (NbB_2), and lanthanum boride (LaB_6). Example aspects of silicides include molybdenum disilicide ($MoSi_2$), tungsten disilicide (WSi_2), titanium disilicide ($TiSi_2$), nickel silicide (NiSi), alkali earth silicide (e.g., sodium silicide (NaSi)), alkali-metal silicide (e.g., magnesium silicide (Mg_2Si)), hafnium disilicide ($HfSi_2$), and platinum silicide (PtSi).

[0147] Throughout the disclosure, an elastic modulus (e.g., Young's modulus) and/or a Poisson's ratio is measured using ISO 527-1:2019. Throughout the disclosure, the Young's modulus of the glass-based materials and ceramic-based materials are measured using the resonant ultrasonic spectroscopy technique set forth in ASTM E2001-13, titled "Standard Guide for Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts." In aspects, the foldable substrate **201** can comprise an elastic modulus in a range from 10 GPa to 100 GPa, from 40 GPa to 100 GPa, from 60 GPa to 100 GPa, from 60 GPa to 80 GPa, from 80 GPa to 100 GPa, or any range or subrange therebetween.

[0148] Unless otherwise indicated, transmittance values are measured using a BYK Haze-Gard Dual (BYK Gardner). In aspects, the foldable substrate **201** can be optically transparent. As used herein, "optically transparent" or "optically clear" means an average transmittance of 70% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of a material. In aspects, an "optically transparent material" or an "optically clear material" may have an average transmittance of 75% or more, 80% or more, 85% or more, or 90% or more, 92% or more, 94% or more, 96% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of the material. The average transmittance in the wavelength range of 400 nm to 700 nm is calculated by measuring the transmittance of whole number wavelengths from 400 nm to 700 nm and averaging the measurements.

[0149] As shown in FIGS. **23**, the foldable apparatus **101** and/or **301** comprise the foldable substrate **201** comprising a first major surface **203** and a second major surface **205** opposite the first major surface **203**. As shown in FIGS. **2-3**, the first major surface **203** can extend along a first plane **204*a***. The second major surface **205** can extend along a second plane **204*b***. In aspects, as shown in FIGS. **2-3**, the first major surface **203** may be discontinuous, for example, being separated by the central portion **281** (e.g., with the central portion **281** attaching the first portion **221** to the second portion **231** with a first central surface area **213**). In aspects, as shown, the second plane **204*b*** can be parallel to the first plane **204*a***. As used herein, a substrate thickness **209** is defined between the first major surface **203** and the second major surface **205** as a distance between the first plane **204*a*** and the second plane **204*b*** in the thickness direction **202**. In aspects, the substrate thickness **209** can be 10 micrometers (μm) or more, 25 μm or more, 40 μm or more, 50 μm or more, 60 μm or more, 70 μm or more, 80 μm or more, 90 μm or more, 100 μm or more, 125 μm or more, 150 μm or more, 200 μm or more, 300 μm or more, 2 millimeters (mm) or less, 1 mm or less, 800 μm or less, 500 μm or less, 300 μm or less, 200 μm or less, 180 μm or less, or 160 μm or less. In aspects, the substrate thickness **209** can be in a range from 10 μm to 2 mm, from 25 μm to 2 mm, from 40 μm to 2 mm, from 50 μm to 2 mm, from 60 μm to 2 mm, from 70 μm to 2 mm, from 70 μm to 1 mm, from 70 μm to 800 μm, from 80 μm to 500 μm, from 90 μm to 500 μm, from 100 μm to 200 μm, from 125 μm to 200 μm, from 150 μm to 200 μm, from 150 μm to 160 μm, or any range or subrange therebetween.

[0150] As shown in FIG. **2**, the first portion **221** of the foldable substrate **201** can comprise a first surface area **223** and a second surface area **225** opposite the first surface area **223**. The first portion **221** will now be described with reference to the foldable apparatus **101** of FIG. **2** with the understanding that such description of the first portion **221**, unless otherwise stated, can also apply to any aspect of the disclosure. In aspects, as shown, the first surface area **223** can comprise a planar surface, and/or the second surface area **225** of the first portion **221** can comprise a planar surface. In further aspects, as shown, the second surface area **225** can be parallel to the first surface area **223**. In aspects, as shown, the first major surface **203** can comprise the first surface area **223** and the second major surface **205** can comprise the second surface area **225**. In further aspects, the first surface area **223** can extend along the first plane **204*a***. In further aspects, the second surface area **225** can extend along the second plane **204*b***. In aspects, the substrate thickness **209** can correspond to the distance between the first surface area **223** of the first portion **221** and the second surface area **225** of the first portion **221**. In aspects, the substrate thickness **209** can be substantially uniform across the first surface area **223**. In aspects, a first thickness defined between the first surface area **223** and the second surface area **225** can be within one or more of the ranges discussed above with regard to the substrate thickness **209**. In further aspects, the first thickness can comprise the substrate thickness **209**. In further aspects, the first thickness of the first portion **221** may be substantially uniform between the first surface area **223** and the second surface area **225** across its corresponding length (i.e., in the direction **106** of the length **105** of the foldable apparatus) and/or its corresponding width (i.e., in the direction **104** of the width **103** of the foldable apparatus). As discussed above, it is to be understood that the foldable apparatus **101** and/or **301** shown in FIGS. **2-3** can also comprise a first portion **221** similar to or identical to that described above in this paragraph attached to the central portion **281**.

[0151] As shown in FIG. **2**, the second portion **231** of the foldable substrate **201** can comprise a third surface area **233** and a fourth surface area **235** opposite the third surface area **233**. The second portion **231** will now be described with reference to the foldable apparatus **101** of FIG. **2** with the understanding that such description of the second portion **231**, unless otherwise stated, can also apply to any aspect of the disclosure. In aspects, as shown, the third surface area **233** of the second portion **231** can comprise a planar surface, and/or the fourth surface area **235** of the second portion **231** can comprise a planar surface. In further aspects, the third surface area **233** of the second portion **231** can be in a common plane with the first surface area **223** of the first portion **221**. In further aspects, as shown, the fourth surface area **235** can be parallel to the third surface area **233**. In further aspects, the fourth surface area **235** of the second portion **231** can be in a common plane with the second surface area **225** of the first portion **221**. A second thickness can be defined between the third surface area **233** of the second portion **231** and the fourth surface area **235** of the second portion **231**. In aspects, the second thickness can be within the range discussed above with regard to the substrate thickness **209**. In further aspects, the second thickness can comprise the substrate thickness **209**. In further aspects, as shown, the second thickness can be substantially equal to the substrate thickness **209**. In aspects, the second thickness of the second portion **231** may be substantially uniform between the third surface area **233** and the fourth surface area **235**. As discussed above, it is to be understood that the foldable apparatus **101** and/or **301** shown in FIGS. **2-3** can also comprise a second portion **231** similar to or identical to that described above in this paragraph attached to the central portion **281**.

[0152] As shown in FIGS. **2-3**, the foldable substrate **201** comprises a central portion **281** positioned between the first portion **221** and the second portion **231**. In aspects, as shown in FIGS. **2-3**, the central portion **281** can comprise a first central surface area **213** and/or a second central surface area **243** opposite the first central surface area **213**. In aspects, as shown in FIGS. **2-3**, the central portion can further comprise a first transition surface area **215** and/or a second transition surface area **217** attaching the first central surface area **213** to the first portion **221** or the second portion **231**, respectively. In aspects, although not labeled, a transition width of the first transition surface area **215** and/or the second transition surface area **217** (between the first central surface area **213** and the first portion **221** or the second portion **231**) in the direction **106** can be 100 μm or more, 200 μm or more, 300 μm or more, 500 μm or more, 700 μm or more, 1 mm or more, 7 mm or less, 6 mm or less, 5 mm or less, 4 mm or less, 3 mm or less, 1 mm or less, 800 μm or less, or 600 μm or less. In further aspects, the transition width can be in a range from 100 μm to 7 mm, from 100 μm to 6 mm, from 100 μm to 5 mm, from 100 μm to 4 mm, from 200 μm to 3 mm, from 300 μm to 1 mm, from 500 μm to 1 mm, from 500 μm to 800 μm, from 500 μm to 600 μm, or any range or subrange therebetween.

[0153] In aspects, as shown in FIG. **2**, the central portion **281** comprises a central thickness **289** defined a minimum thickness of the foldable substrate **201** in a thickness direction **202** of the substrate thickness **209** for the central portion **281** of the foldable substrate **201**. Consequently, the central thickness **289** is less than the substrate thickness **209**. For example, as shown in FIG. **2**, the central thickness **289** occurs between a first central surface area **213** and a second central surface area **243**. Also, the first central surface area **213** excludes the plurality of protrusions **251** (discussed below) extending therefrom. In further aspects, the first central surface area **213** (excluding the plurality of protrusions **251**) can be substantially planar and/or extend along a third plane **204***c* that can, in even further aspects, be substantially parallel to the first plane **204***a* and/or the second plane **204***b*.

[0154] In aspects, the central thickness **289** can be 1 μm or more, 5 μm or more, 10 μm or more, 25 μm or more, 40 μm or more, 120 μm or less, 100 μm or less, 80 μm or less, 60 μm or less, or 50 μm or less. In aspects, the central thickness **289** can be in a range from 1 μm to 120 μm, from 5 μm to 120 μm, from 10 μm to 120 μm, from 10 μm to 120 μm, from 25 μm to 120 μm, from 25 μm to 100 μm, from 25 μm to 80 μm, from 25 μm to 60 μm, from 40 μm to 60 μm, or any range or subrange therebetween. In aspects, the central thickness **289** can be less than the substrate thickness **209** by 10 μm or more, 20 μm or more, 30 μm or more, 40 μm or more, 50 μm or more, or 60 μm or more. In aspects, the central thickness **289** as a percentage of the substrate thickness **209** can be 0.5% or more, 1% or more, 2% or more, 5% or more, 6% or more, 10% or more, 25% or more, 40% or more, 50% or more, 66% or more, 75% or more, 80% or more, 90% or less, 88% or less, 85% or less, 82% or less, 80% or less, 80% or less, 75% or less, 66% or less, 60% or less, 45% or less, 30% or less, 20% or less, 13% or less, 10% or less, or 8% or less. In aspects, the central thickness **289** as a percentage of the substrate thickness **209** can be in a range from 0.5% to 40%, from 0.5% to 30%, from 0.5% to 20%, from 0.5% to 13%, from 1% to 13%, from 1% to 10%, from 2% to 10%, from 2% to 8%, from 5% to 8%, from 6% to 8%, or any range or subrange therebetween. Alternatively, in aspects, the central thickness **289** as a percentage of the substrate thickness **209** can be in a range from 10% to 90%, from 25% to 90%, from 40% to 88%, from 50% to 88%, from 66% to 85%, from 75% to 85%, from 80% to 82%, or any range or subrange therebetween.

[0155] As shown in FIGS. **2-3**, the first central surface area **213** can be recessed from the first major surface **203** by a first distance **219**. In further aspects, the first distance **219** can be 30 μm or more, 40 μm or more, 50 μm or more, 70 μm or more, 100 μm or more, 3 mm or less, 1 mm or less, 800 μm or less, 500 μm or less, 300 μm or less, 100 μm or less, or 60 μm or less. In further aspects, the first distance **219** can be in a range from 30 μm to 3 mm, from 30 μm to 1 mm, from 30 μm to 800 μm, from 30 μm to 500 μm, from 40 μm to 300 μm, from 50 μm to 100 μm, from 50 μm to 60 μm, or any range or subrange therebetween. In aspects, the first distance **219** can correspond to a distance (in the thickness direction **202**) between the first plane **204***a* and the third plane **204***c*. In aspects, as shown, the second central surface area **243** can be part of the second major surface **205**. In aspects, as shown, the second central surface area **243** can be flush with the second major surface **205**.

[0156] The inventors of the present application have unexpectedly determined that providing a plurality of protrusions can improve impact resistance (e.g., as measured in the Quasi-Static Puncture Test) while allowing the foldable substrate and/or foldable substrate to still attain low parallel plate distances. Specifically, as discussed below with reference to FIG. **24**, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness with the same parallel plate distance (e.g., minimum parallel plate distance) (where the parallel plate distance and impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance without negatively impacting foldability (e.g., parallel plate distance). Also, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness equal to a weighted average thickness (defined below) (where the impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance beyond what would be achieved for a substrate with the same weighted average thickness.

[0157] FIGS. **2-3** show cross-sectional views of the foldable apparatus **101** and/or **301** comprising a plurality of protrusions **251** and/or **351** in accordance with aspects of the disclosure. In aspects, as shown in FIGS. **2-3**, the plurality of protrusions **251** and/or **351** can extend from the first central surface area **213**, although the plurality of protrusions can extend from both sides of the foldable substrate in further aspects. In further aspects, as shown, the central portion **281** including the protrusions **251** and/or **351** is defined based on the local thickness profile of the first central surface area **213** excluding the plurality of protrusions **251** and/or **351**, where the thickness increases from a local thickness equal to the central thickness (e.g., central thickness **289** shown in FIG. **2**). In aspects, as shown in FIG. **2**, a local thickness of the central portion **281** (e.g., profile of first central surface area **213**) excluding the plurality of protrusions **351** can be substantially constant across the first central surface area **213** (e.g., excluding any transition surface areas).

[0158] Throughout the disclosure, a protrusion of the plurality of protrusions extends from the first central surface area by at least 5 μm in the thickness direction. For example, with reference to FIG. **2**, protrusion **253***a* of the plurality of protrusions **251** extends from the first central surface area **213** (excluding the plurality of protrusions **251**—e.g., third plane **204***c*) in the thickness direction **202** by at least 5 μm (i.e., protrusion height **259** is greater than 5 μm). In aspects, the protrusions **253***a*-**253***c* and/or **353***a*-**353***d* of the plurality of protrusions **251** and/or **351** can extend from the first central surface area **213** in the thickness direction **202** by at least 10 μm, 20 μm or more, 25 μm or more, 30 μm or more, 35 μm or more, 40 μm or more, or 50 μm or more. As used herein, a protrusion height of a protrusion of the plurality of protrusions is defined as a maximum distance between the first central surface area and an upper surface of the corresponding protrusion in the thickness direction. For example, with reference to FIG. **2**, the protrusion height **259** of the protrusion **253***a* of the plurality of protrusions **251** is a maximum distance in the thickness direction **202** between the first central surface area **213** (excluding the plurality of protrusions **251**—e.g., third plane **204***c*) and the upper surface **257***a*-**257***c* (e.g., outer periphery) of the corresponding protrusion **253***a*. In aspects, as shown in FIGS. **2-3**, the protrusion height **259** and/or **359** can be substantially uniform across the plurality of protrusions **251** and/or **351**, although the protrusion heights may vary among the plurality of protrusions in other aspects.

[0159] In aspects, as shown in FIGS. **2-3**, the first distance **219** that the first central surface area **213** is recessed from the first major surface **203** can be greater than or equal to the protrusion height **259** and/or **359** of one or more protrusions **253***a*-**253***c* and/or **353***a*-**353***d* (e.g., all) of the plurality of protrusions **251** and/or **351**. In further aspects, a ratio of the protrusion height **259** and/or **359** to the first distance **219** (as a percentage) can be 30% or more, 40% or more, 50% or more, 66% or more, 75% or more, 80% or more, 85% or more, 90% or more, 95% or more, 100% or less, 98% or less, 95% or less, 92% or less, 90% or less, 85% or less, 80% or less, 75% or less, 70% or less, 65% or less, 60% or less, or 50% or less. In further aspects, a ratio of the protrusion height **259** and/or **359** to the first distance **219** (as a percentage) can be in a range from 30% to 100%, from 40% to 98%, from 50% to 95%, from 66% to 92%, from 75% to 90%, from 80% to 85%, or any range or subrange therebetween. In further aspects, as shown in FIG. **3**, the protrusion height **359** can be less than the first distance **219**. Alternatively, as shown in FIG. **2**, the protrusion height **259** can be substantially equal to the first distance **219**. In aspects, a combined thickness of the central thickness **289** and the protrusion height **259** and/or **359** can be less than or equal to the substrate thickness **209**. In further aspects, as shown in FIG. **3**, the combined thickness of the central thickness **289** and the protrusion height **359** can be less than the substrate thickness **209**. Alternatively, as shown in FIG. **2**, the combined thickness of the central thickness **289** and the protrusion height **259** can be substantially equal to the substrate thickness **209**.

[0160] In aspects, as shown in FIGS. **2-3** and **20-21**, the shape of a cross-section of one or more protrusions **253***a*-**253***c* and/or **353***a*-**353***d* of the plurality of protrusions **251** and/or **351** can be substantially polygonal (e.g., linear and/or quadrilateral), although the shape of the cross-section can be curved (e.g., elliptical), curvilinear, or a combination thereof in further aspects. In aspects, a cross-sectional shape of a protrusion of the plurality of protrusions can have rounded corners (e.g., between inclined, side surfaces and an upper surface therebetween—rather than the angular corners shown herein). Providing rounded corners for the cross-sectional shape of a tooth of the plurality of protrusions can decrease stress concentrations at the corners of the protrusion, which can decrease a maximum bending stress associated with folding to a predetermined parallel plate distance and/or increase a reliability of folding the foldable substrate and/or foldable apparatus. Also, providing a plurality of protrusions (e.g., comprising substantially the substrate thickness) can increase a puncture resistance of the central portion (e.g., due to the increased thickness of the plurality of protrusions relative to the first central surface area **213**) while the central portion (excluding the plurality of protrusions) can still facilitate folding of the foldable apparatus and/or foldable substrate. In further aspects, providing a plurality of substantially constant local thicknesses (e.g., substantially equal to the central thickness **289**) between corresponding adjacent pairs of protrusions of the plurality of protrusions can simplify manufacturing, for example, enabling the local thickness between an adjacent pair of protrusions to be formed in a single etching step (e.g., with the portions corresponding to the adjacent pair of protrusions being masked).

[0161] Throughout the disclosure, the upper surface of a protrusion is defined as portions of the surface of the protrusion that is within 5 μm in the thickness direction of an outer periphery of the protrusion corresponding to the protrusion height between the first central surface area and the corresponding outer periphery of the corresponding protrusion. With reference to FIG. **2**, the upper surface **257***a* of the protrusion **253***a* is the portion of the outer surface **255***a* of the protrusion that is within 5 μm in the thickness direction **202** (e.g., vertical distance in FIG. **2**) of an outer periphery (e.g., the portion of the outer surface **255***a* extending along the first plane **204***a*) that is positioned the protrusion height **259** from the first central surface area **213**. Consequently, the upper surface **257***a* of protrusion **253***a* includes the substantially planar portion (e.g., extending along the first plane **204***a*) and additional portions of the outer surface **255***a* to either side that are within 5 μm in the thickness direction **202** of the substantially planar portion corresponding to the outer periphery of the protrusion **253***a*. For simplicity, the upper surface **257***a* is shown as being substantially coextensive with the substantially planar portion with the understanding that the outer surface may in-fact include a portion of the upper surface to either side (e.g., curved and/or inclined portions adjacent to the outer periphery).

[0162] In aspects, as shown in FIGS. **2-6**, an upper width **254***a*, **354***a*, and/or **354***b* of an upper surface **257***a*, **357***a*, and/or **357***b* of a protrusion **253***a*, **353***a*, and/or **353***b* of the plurality of protrusions **251** and/or **351** is measured in the direction **106** between the first portion **221** and the second portion **231**. In aspects, the upper width **254***a*, **354***a*, and/or **354***b* can be 20 μm or more, 30 μm or more, 40 μm or more, 50 μm or more, 65 μm or more, 80 μm or more, 100 μm or more, 150 μm or more, 200 μm or more, 250 μm or more, 300 μm or more, 400 μm or more, 500 μm or more, 1 mm or less, 800 μm or less, 600 μm or less, 500 μm or less, 400 μm or less, 310 μm or less, 260 μm or less, 180 μm or less, 130 μm or less, 100 μm or less, or 80 μm or less. In aspects, the upper width **254***a*, **354***a*, and/or **354***b* can be in a range from 20 μm to 1 mm, from 30 μm to 800 μm, from 40 μm to 600 μm, from 50 μm to 500 μm, from 65 μm to 400 μm, from 80 μm to 310 μm, from 100 μm to 260 μm, from 150 μm to 180 μm, or any range or subrange therebetween. In preferred aspects, the upper width **254***a*, **354***a*, and/or **354***b* can be from 20 μm to 1 mm, from 80 μm to 310 μm, or from 150 μm to 250 μm. In aspects, as shown in FIG. **3**, the upper width **354***a* of a protrusion **353***a* can be substantially equal to the upper width **354***b* of an adjacent protrusion **353***b* of the plurality of protrusions, and/or the upper width **354***a* and/or **354***b* of each protrusion **353***a*-**353***d* of the plurality of protrusions **351** can be substantially the same, although in other aspects, an upper width of protrusions can vary in other aspects, for example, with protrusions closer to the fold plane **109** having smaller upper widths than protrusions further from the fold plane **109**. Similarly, as shown in FIGS. **4-6**, the upper width **254***a* (of upper surface **257***a*, **257***d*, and/or **257***g*) of a protrusion (corresponding to outer surface **255***a*, **255***d*, and/or **255***g*) can be substantially equal to the upper width **254***b* and/or **254***c* (of upper surface **257***b*, **257***c*, **257***e*, **257***f*, **257***h* and/or **257***i*) of other protrusions (corresponding to protrusions **255***b*, **255***c*, **255***e*, **255***f*, **255***h*, and/or **255***i*) of the plurality of protrusions. In aspects, as shown in FIG. **3**, the midline (e.g., dashed line, fold plane **109**) may not impinge a protrusion of the plurality of protrusions **351**. Alternatively, in aspects, as shown in FIG. **2**, the midline (e.g., dashed line, fold plane **109**) may impinge a protrusion **253***b* of the plurality of protrusions **251**. Providing a plurality of protrusions arranged such that there is not a protrusion of the plurality of protrusions impinged by the midline (e.g., fold plane **109**) can decrease a bend-induced stress on the foldable substrate.

[0163] In aspects, as shown in FIGS. **2-6**, a full width **252***a*, **352***a*, and/or **352***b* of a protrusion **253***a*, **353***a*, and/or **353***b* of the plurality of protrusions **251** and/or **351** is measured as a maximum width of the protrusion (e.g., outer surface **255***a*-**255***c*, **255***a*-**255***i*, and/or **355***a*-**355***d*) in the direction **106** between the first portion **221** and the second portion **231**. In aspects, an absolute value of a difference between the upper width **254***a*, **354***a*, and/or **354***b* and the full width **252***a*, **352***a*, and/or **352***b* can be 1 mm or less, 800 μm or less, 500 μm or less, 300 μm or less, 250 μm or less, 200 μm or less, 180 μm or less, 150 μm or less, 10 μm or more, 25 μm or more, 40 μm or more, 60 μm or more, 80 μm or more, 100 μm or more, 120 μm or more, or 140 μm or more. In aspects, an absolute value of a difference between the upper width **254***a*, **354***a*, and/or **354***b* and the full width **252***a*, **352***a*, and/or **352***b* can be in a range from 10 μm to 1 mm, from 10 μm to 800 μm, from 25 μm to 500 μm, from 25 μm to 300 μm, from 40 μm to 250 μm, from 60 μm to 200 μm, from 80 μm to 180 μm, from 100 μm to 150 μm, from 120 μm to 150 μm, or any range or subrange therebetween. In aspects, the full width can be within one or more of the ranges discussed above for the upper width. In aspects, as shown in FIG. **3**, the full width **352***a* of a protrusion **353***a* can be substantially equal to the full width **352***b* of an adjacent protrusion **353***b* of the plurality of protrusions, and/or the full width **352***a* and/or **352***b* of each protrusion **353***a*-**353***d* of the plurality of protrusions **351** can be substantially the same, although in other aspects, an full width of protrusions can vary in other aspects, for example, with protrusions closer to the fold plane **109** having smaller full widths than protrusions further from the fold plane **109**. Similarly, as shown in FIGS. **4-6**, the full width **252***a* of a protrusion (corresponding to outer surface **255***a*, **255***d*, and/or **255***g*) can be substantially equal to the full width **252***b* and/or **252***c* of other protrusions (corresponding to protrusions **255***b*, **255***c*, **255***e*, **255***f*, **255***h*, and/or **255***i*) of the plurality of protrusions.

[0164] In aspects, as shown in FIGS. **2-6**, a gap width **256***a*, **356***a*, and/or **356***b* can be defined between an adjacent pair of protrusions (e.g., protrusions **253***a* and **253***b*, **353***a* and **353***b*, and/or **353***b* and **353***c*). For example, with reference to FIG. **3**, gap width **356***a* is measured between the adjacent pair of protrusions **353***a* and **353***b*. Likewise, gaps associated with gap width **356***a* and **356***b* are adjacent to protrusion **353***b*. In further aspects, as shown in FIGS. **2-6**, the gap width **256***a*-**256***b* and/or **356***a*-**356***b* between an adjacent pair of protrusions can be substantially the same for all adjacent pairs of protrusions (e.g., of the plurality of protrusions) in the central portion **281**. Alternatively, although not shown, distances between adjacent pairs of protrusions for different adjacent pairs of protrusions can be different as the distance of the adjacent pair of protrusions from the midline (e.g., fold plane **109**) changes. For example, the distance between a first adjacent pair of protrusions can be less than a distance between a second adjacent pair of protrusions, where the first adjacent pair of protrusions is closer to the midline (e.g., dashed line, fold plane **109**) than the second adjacent pair of protrusions is to the midline. Alternatively, for example, the distance between adjacent pairs of protrusions can be greater than a distance between a second adjacent pair of protrusions, wherein the first adjacent pair of protrusions is closer to the midline (e.g., dashed line, fold plane **109**) than the second adjacent pair of protrusions is to the midline. In further aspects, the gap width **256***a*-**256***b* and/or **356***a*-**356***b* can be 10 μm or more, 50 μm or more, 80 μm or more, 100 μm or more, 120 μm or more, 150 μm or more, 200 μm or more, 1 mm or less, 800 μm or less, 500 μm or less, 400 μm or less, 300 μm or less, 250 μm or less, 200 μm or less, or 180 μm or less. In further aspects, the gap width **256***a*-**256***b* and/or **356***a*-**356***b* can be in a range from 10 μm to 1 mm, from 50 μm to 800 μm, from 80 μm to 500 μm, from 100 μm to 400 μm, from 120 μm to 300 μm, from 150 μm to 250 μm, or any range or subrange therebetween. Although not explicitly labeled, a minimum distance between the upper surfaces of adjacent protrusions can be within one or more of the ranges discussed for the gap width. The minimum distance between the upper surfaces of adjacent protrusions can be from 150 μm to 1 mm, from 200 μm to 800 μm, from 250 μm to 600 μm, from 300 μm to 500 μm, or any range or subrange therebetween.

[0165] FIGS. **4-6** show various patterns for the plurality of protrusions in foldable apparatus **101** and/or **301** and the first central surface area **213**. In aspects, as shown in FIG. **4**, the plurality of protrusions can be aligned in a row extending in the direction **106** (e.g., between the first portion **221** and the second portion **231** shown in FIGS. **2-3**). In further aspects, as shown, the plurality of protrusions can be arranged in a single row (e.g., one-dimensional row). In further aspects, a length **421** of one or more of the protrusions **253***a*-**253***c* in a direction **104** (perpendicular to the direction **106**), as a percentage of the width **103** of the foldable substrate **201** and/or the foldable apparatus **101** and/or **301**, can be 50% or more, 66% or more, 75% or more, 80% or more, 85% or more, 90% or more, 92% or more 95% or more, 100% or less, 99% or less, 98% or less, 95% or less, 92% or less, 90% or less, 85% or less, 80% or less, or 75% or less. In further aspects, a length **421** of one or more of the protrusions **253***a*-**253***c* in a direction **104** (perpendicular to the direction **106**), as a percentage of the width **103** of the foldable substrate **201** and/or the foldable apparatus **101** and/or **301**, can be from 50% to 100%, from 66% to 99%, from 75% to 98%, from 80% to 95%, from 85% to 92%, from 90% to 92%, or any range or subrange therebetween. As indicated by portions **1605** and **1607** in FIG. **16**, the plurality of protrusions may not extend all the way to the ends (in direction **104**) of the central portion, although the plurality of protrusions can extend for the entire width of the foldable substrate and/or foldable apparatus in the central portion in further aspects.

[0166] In aspects, as shown in FIGS. **4-6**, one or more protrusions (e.g., protrusions **253***a*-**253***c* and/or protrusions **253***a*-**253***i*) of the plurality of protrusions comprise an upper width (e.g., upper width **254***a*-**254***c*) of the upper surface (e.g., upper surface **257***a*-**257***c* and/or upper surface **257***a*-**257***i*) within one or more of the corresponding ranges for the upper width discussed above. In aspects, as shown in FIGS. **4-6**, one or more protrusions (e.g., protrusions **253***a*-**253***c* and/or protrusions **253***a*-**253***i*) of the plurality of protrusions comprise a full width (e.g., full width **252***a*-**252***c*) of the outer surface (e.g., outer surface **255***a*-**255***c* and/or outer surface **255***a*-**255***i*) within one or more of the corresponding ranges for the full width discussed above. In aspects, as shown in FIGS. **4-6**, a gap width **256***a*-**256***b* between adjacent pairs of protrusions in the direction **106** (or the full width) can be within one or more of the corresponding ranges (e.g., gap width or full width, respectively) discussed above.

[0167] As shown in FIGS. **5-6**, the plurality of protrusions can be arranged in a two-dimensional array with rows extending in the direction **106** (between the first portion and the second portion) and columns extending in the direction **104** (perpendicular to the direction **104**), where adjacent rows and/or columns can be aligned or offset. In aspects, as shown, a column **511**, **513**, **515**, **611**, **621**, or **631** can comprise three or more protrusions, and/or each row can comprise at least three protrusions. In aspects, as shown in FIG. **6**, the plurality of protrusions in a first column **611** can be aligned with corresponding protrusions of a second column **621** of the plurality of columns in the two-dimensional array (e.g., an offset **531** in FIG. **5** of 0). In aspects, as shown in FIG. **5**, the plurality of protrusions in a first column **511** can be offset from the plurality of protrusions in a second column **513** by an offset **531**. In aspects, the offset **531**, as a percentage of the upper length **623**, can be 15% or more, 30% or more, 40% or more, 50% or more, 60% or more, 66% or more, 75% or more, 125% or less, 100% or less, 85% or less, 70% or less, 60% or less, 50% or less, 40% or less, 33% or less, or 25 or less. In aspects, the offset **531**, as a percentage of the upper length **623**, can be in a range from 15% to 125%, from 30% to 100%, from 30% to 85%, from 40% to 70%, from 50% to 60%, or any range or subrange therebetween.

[0168] In aspects, as shown in FIGS. **5-6**, a protrusion (corresponding to outer surface **255***d*) of the plurality of protrusions comprises an upper length **523** and/or **623** of the upper surface **257***d*. In further aspects, as shown, the upper length **523** and/or **623** can be greater than or equal to the upper width **254***a*. In further aspects, the upper length **523** and/or **623** can be 1 mm or more, 2 mm or more, 3 mm or more, 4 mm or more, 5 mm or more, 15 mm or less, 10 mm or less, 8 mm or less, 7 mm or less, 6 mm or less, or 5 mm or less. In aspects, the upper length **523** and/or **623** can be from 1 mm to 15 mm, from 2 mm to 10 mm, from 2 mm to 8 mm, from 3 mm to 7 mm, from 3 mm to 6 mm, from 4 mm to 5 mm, or any range or subrange therebetween. In aspects, as shown, a protrusion of the plurality of protrusions comprises a full length **521** and/or **613** of the outer surface **255***d* that can be within one more of the range discussed above for the upper length. In aspects, an absolute value of a difference between the full length **521** and/or **613** and the upper length **523** and/or **623** can be substantially equal to an absolute value of a difference between the full width **252***a* and the upper width **254***a*.

[0169] In aspects, as shown in FIGS. **5-6**, an adjacent pair of protrusions in the same column (e.g., column **511**, **513**, **515**, **611**, **621**, or **631**) can be separated by a gap length **525** and/or **625** in the direction **104**. In aspects, as shown in FIGS. **5-6**, the upper surfaces **257***a*-**257***i* of an adjacent pair of protrusions in the same column (e.g., column **511**, **513**, **515**, **611**, **621**, or **631**) can be separated by a minimum distance **527** in the direction **104**. In aspects, the gap length **625** and/or the minimum distance **527** can be within one or more of the ranges discussed above for the gap width **256***a*, **256***b*, **356***a*, and/or **356***b*. In aspects, an absolute value of a difference between the minimum distance **527** and the gap length **625** can be substantially equal to an absolute value of a difference between the full width **252***a* and the upper width **254***a*.

[0170] Throughout the disclosure, a "total protrusion area" is a sum of an area of the upper surface of each protrusion of the plurality of protrusions. For example, with reference to FIG. **4**, the total protrusion area (for protrusions in the region shown) is the sum of an area of upper surface **257***a* for protrusion **253***a*, upper surface **257***b* for protrusion **253***b*, and upper surface **257***c* for protrusion **253***c*. With reference to FIGS. **5-6**, the total protrusion area (for protrusions in the region shown) is the sum of the surface area of upper surfaces **257***a*-**257***i*. Throughout the disclosure, a "total central area" is an area of the central portion in a plane perpendicular to the thickness direction and impinging the first central surface area. For example, with reference to FIGS. **4-6**, the total central area is the entire area shown (that is all part of the central portion) not just the portions of the first central surface area **213** since the central portion includes portions where the plurality of protrusions are. With reference to FIG. **2**, the total central area is an area of the central portion projected onto the third plane **204***c* that is perpendicular to the thickness direction **202** and impinges the first central surface area **213**; again, the total central area is the central width **287** of the central portion times the length (dimension not shown in FIG. **2**—see direction **104** in FIGS. **4-6** and/or width **103** of the foldable substrate **201**

and/or foldable apparatus **101** and/or **301**). As used herein, an "area ratio" is the total protrusion area divided by the total central area. In aspects, the area ratio can be 0.10 or more, 0.15 or more, 0.20 or more, 0.25 or more, 0.30 or more, 0.35 or more, 0.40 or more, 0.70 or less, 0.65 or less, 0.60 or less, 0.55 or less, 0.50 or less, 0.45 or less, or 0.40 or less. In aspects, the area ratio can be from 0.10 to 0.70, from 0.15 to 0.65, from 0.20 to 0.60, from 0.20 to 0.55, from 0.25 to 0.50, from 0.30 to 0.45, from 0.35 to 0.40, or any range or subrange therebetween. In preferred aspects, the area ratio can be in a range from 0.10 to 0.70, from 0.20 to 0.60, or from 0.25 to 0.50. As discussed herein, providing an area ratio from 0.10 to 0.70 (e.g., from 0.20 to 0.60, or from 0.25 to 0.50) can unexpectedly provide improved impact resistance (e.g., as measured in the Quasi-Static Puncture Test), for example, relative to a reference substrate with the same parallel plate distance or with the same weighted average thickness.

[0171] Aspects of the disclosure can comprise a consumer electronic product. The consumer electronic product can comprise a front surface, a back surface, and a side surface (s). The consumer electronic product can further comprise electrical components at least partially within the housing. The electrical components can comprise a controller, a memory, and a display. The display can be at or adjacent to the front surface of the housing. The display can comprise liquid crystal display (LCD), an electrophoretic displays (EPD), an organic light-emitting diode (OLED) display, or a plasma display panel (PDP). The consumer electronic product can comprise a cover substrate disposed over the display. In aspects, at least one of a portion of the housing or the cover substrate comprises the foldable apparatus and/or the foldable substrate discussed throughout the disclosure. The consumer electronic product can comprise a portable electronic device, for example, a smartphone, a tablet, a wearable device, or a laptop.

[0172] The foldable apparatus disclosed herein may be incorporated into another article, for example, an article with a display (or display articles) (e.g., consumer electronics, including mobile phones, tablets, computers, navigation systems, wearable devices (e.g., watches), and the like), architectural articles, transportation articles (e.g., automotive, trains, aircraft, sea craft, etc.), appliance articles, or any article that may benefit from some transparency, scratch-resistance, abrasion resistance or a combination thereof. An exemplary article incorporating any of the foldable apparatus disclosed herein is shown in FIGS. **8-9**. Specifically, FIGS. **8-9** show a consumer electronic device **800** including a housing **802** having front **804**, back **806**, and a side surface **808**. Although not shown, the consumer electronic device can comprise electrical components that are at least partially inside or entirely within the housing. For example, electrical components include at least a controller, a memory, and a display. As shown in FIGS. **8-9**, the display **810** can be at or adjacent to the front surface of the housing **802**. The consumer electronic device can comprise a cover substrate **812** at or over the front surface of the housing **802** such that it is over the display **810**. In aspects, at least one of the cover substrate **812** or a portion of housing **802** may include any of the foldable apparatus disclosed herein, for example, the foldable substrate.

[0173] Also, FIG. **10** schematically shows a perspective view of a consumer electronic product **1001** that is foldable. The consumer electronic product **1001** can include the foldable apparatus **101** and/or **301** and/or the foldable substrate **201** in accordance with aspects of the present disclosure. As shown, the consumer electronic product **1001** can include a front surface **1003** and a side surface **1005**. The consumer electronic product **1001** can include electronic components, including a display **1002** that can be viewed through the front surface **1003** and/or at the front surface **1003**. In aspects, as shown, the consumer electronic product **1001** can be folded in a direction **1012** to form a folded configuration that brings a first end **1027** and a second end **1037** (opposite the first end **1027**) closer together (than in the unfolded configuration). Additionally, as shown, the consumer electronic product **1001** can be folded so that the front surface **1003** and/or display **1002** faces itself, although the consumer electronic product could be folded opposite the direction **1012** so that the front surface **1003** is on the outside of the consumer electronic product in the folded configuration. As discussed above with reference to FIG. **1**, the consumer electronic product **1001** shown in FIG. **10** can be folded about the fold axis **102**, where a central portion **1081** is located. The central portion **1081** can include the central portion **281** (e.g., of the foldable apparatus **101** and/or **301** discussed above with reference to FIGS. **2-3**. As shown in FIG. **10**, the central portion is positioned between a first portion **1021** including the first end **1027** and a second portion **1031** including the second end **1037**. A location of the fold axis **102** can determine a first distance **1013** between the first end **1027** and the fold axis **102** (e.g., in direction **106**) relative to a second distance **1015** between the second end **1037** and the fold axis **102** (e.g., in direction **1008**). A total length of the consumer electronic product (e.g., length **105** in FIG. **1**) can be the sum of the first distance **1013** and the second distance **1015**). Also, as shown, the consumer electronic product is depicted as being in a folded or partially folded configuration with an angle A formed by front surface **1003** about the fold axis **102**.

[0174] In aspects, the foldable substrate **201** comprising a glass-based substrate and/or a ceramic-based substrate can comprise one or more compressive stress regions. In aspects, a compressive stress region may be created by chemically strengthening. Chemically strengthening may comprise an ion exchange process, where ions in a surface layer are replaced by—or exchanged with—larger ions having the same valence or oxidation state. Methods of chemically strengthening will be discussed later. Without wishing to be bound by theory, chemically strengthening the first portion **221**, the second portion **231**, the central portion **281**, and/or the central portion **281** can enable good impact and/or puncture resistance (e.g., resists failure for a pen drop height of about 15 centimeters (cm) or more, about 20 cm or more, about 50 cm or more). Without wishing to be bound by theory, chemically strengthening the first portion **221**, the second portion **231**, the central portion **281** and/or the central portion **281** can enable small (e.g., smaller than about 10 mm or less, about 5 mm or less, or about 3 mm or less) bend radii because the compressive stress from the chemical strengthening can counteract the bend-induced tensile stress on the outermost surface of the substrate. A compressive stress region may extend into a portion of the first portion and/or the second portion for a depth called the depth of compression (DOC). As used herein, depth of compression means the depth at which the stress in the chemically strengthened substrates and/or portions described herein changes from compressive stress to tensile stress. Depth of compression may be measured by a surface stress meter or a scattered light polariscope (SCALP, wherein values reported herein were made using SCALP-5 made by Glasstress Co., Estonia) depending on the ion exchange treatment and the thickness of the article being measured. Where the stress in the substrate and/or portion is generated by exchanging potassium ions into the substrate, a surface stress meter, for example, the FSM-6000 (Orihara Industrial Co., Ltd. (Japan)), is used to measure depth of compression. Unless specified otherwise, compressive stress (including surface CS) is measured by surface stress meter (FSM) using commercially available instruments, for example the FSM-6000, manufactured by Orihara. Surface stress measurements rely upon the accurate measurement of the stress optical coefficient (SOC), which is related to the birefringence of the glass. Unless specified otherwise, SOC is measured according to Procedure C (Glass Disc Method) described in ASTM standard C770-16, entitled "Standard Test Method for Measurement of Glass Stress-Optical Coefficient," the contents of which are incorporated herein by reference in their entirety. Where the stress is generated by exchanging sodium ions into the substrate, and the article being measured is thicker than about 400 μm, SCALP is used to measure the depth of compression and central tension (CT). Where the stress in the substrate and/or portion is generated by exchanging both potassium and sodium ions into the substrate and/or portion, and the article being measured is thicker than about 400 μm, the depth of compression and CT are measured by SCALP. Without wishing to be bound by theory, the exchange depth of sodium may indicate the depth of compression while the exchange depth of potassium ions may indicate a change in the magnitude of the compressive stress (but not the change in stress from compressive to tensile). The refracted near-field (RNF; the RNF method is described in U.S. Pat. No. 8,854,623, entitled "Systems and methods for measuring a profile characteristic of a glass sample", which is incorporated herein by reference in its entirety) method also may be used to derive a graphical representation of the stress profile. When the RNF method is utilized to derive a graphical representation of the stress profile, the maximum central tension value provided by SCALP is utilized in the RNF method. The graphical representation of the stress profile derived by RNF is force-balanced and calibrated to the maximum central tension value provided by a SCALP measurement. As used herein, "depth of layer" (DOL) means the depth that the ions have exchanged into the substrate and/or portion (e.g., sodium, potassium). Throughout the disclosure, DOL is measured in accordance with ASTM C-1422. Without wishing to be bound by theory, a DOL is usually greater than or equal to the corresponding DOC. Through the disclosure, when the maximum central tension cannot be measured directly by SCALP (as when the article being measured is thinner than about 400 μm) the maximum central tension can be approximated by a product of a maximum compressive stress and a depth of compression divided by the difference between the thickness of the substrate and twice the depth of compression, wherein the compressive stress and depth of compression are measured by FSM.

[0175] In aspects, the first portion **221** comprising the glass-based portion and/or ceramic-based portion may comprise a first compressive stress region at the first surface area **223** that can extend to a first depth of compression from the first surface area **223**. In aspects, the first portion **221** comprising a first glass-based and/or ceramic-based portion may comprise a second compressive stress region at the second surface area **225** that can extend to a second depth of compression from the second surface area **225**. In aspects, the first depth of compression and/or the second depth of compression as a percentage of the substrate thickness **209** can be about 5% or more, about 10% or more, about 12% or more, about 15% or more, about 30% or less, about 25% or less, about 22% or less, about 20% or less, about 17% or less, or about 15% or less. In aspects, the first depth of compression and/or the second depth of compression as a percentage of the substrate thickness **209** can be in a range from about 5% to about 30%, from about 10% to about 25%, from about 10% to about 22%, from about 12% to about 20%, from about 12% to about 17%, from about 15% to about 17%, or any range or subrange therebetween. In aspects, the first depth of compression and/or the second depth of compression can be about 1 μm or more, about 10 μm or more, about 15 μm or more, about 20 μm or more, about 25 μm or more, about 30 μm or more, about 200 μm or less, about 150 μm or less, about 100 μm or less, about 60 μm or less, about 45 μm or less, about 30 μm or less, or about 20 μm or less. In aspects, the first depth of compression and/or the second depth of compression can be in a range from about 1 μm to about 200 μm, from about 1 μm to about 150 μm, from about 10 μm to about 100 μm, from about 15 μm to about 600 μm, from about 20 μm to about 45 μm, from about 20 μm to about 30 μm, or any range or subrange therebetween. By providing a first portion comprising a first glass-based and/or ceramic-based portion comprising a first depth of compression and/or a second depth of compression in a range from about 1% to about 30% of the first thickness, good impact and/or puncture resistance can be enabled.

[0176] In aspects, the first compressive stress region can comprise a maximum first compressive stress. In aspects, the second compressive stress region can comprise a maximum second compressive stress. In further aspects, the maximum first compressive stress and/or the maximum second compressive stress can be about 100 MegaPascals (MPa) or more, about 300 MPa or more, 400 MPa or more, about 500 MPa or more, about 600 MPa or more, about 700 MPa or more, about 1,500 MPa or less, about 1,200 MPa or less, about 1,000 MPa or less, or about 800 MPa or less. In further aspects, the maximum first compressive stress and/or the maximum second compressive stress can be in a range from about 100 MPa to about 1,500 MPa, from about 100 MPa to about 1,200 MPa, from about 300 MPa to about 1,200 MPa, from about 300 MPa to about 1,000 MPa, from about 400 MPa to about 1,000 MPa, from about 500 MPa to about 1,000 MPa, from about 600 MPa to about 900 MPa, from about 700 MPa to about 800 MPa, or any range or subrange therebetween. By providing a maximum first compressive stress and/or a maximum second compressive stress in a range from about 100 MPa to about 1,500 MPa, good impact and/or puncture resistance can be enabled.

[0177] In aspects, the first portion **221** can comprise a first depth of layer of one or more alkali-metal ions associated with the first compressive stress region. In aspects, the first portion **221** can comprise a second depth of layer of one or more alkali-metal ions associated with the second compressive stress region and the second depth of compression. As used herein, the one or more alkali-metal ions of a depth of layer of one or more alkali-metal ions can include sodium, potassium, rubidium, cesium, and/or francium. In aspects, the one or more alkali ions of the first depth of layer of the one or more alkali ions and/or the second depth of layer of the one or more alkali ions comprises potassium. In aspects, the first depth of layer and/or the second depth of layer as a percentage of the substrate thickness **209** can be about 5% or more, about 10% or more, about 12% or more, about 15% or more, about 30% or less, about 25% or less, about 22% or less, about 20% or less, about 17% or less, or about 15% or less. In aspects, the first depth of layer and/or the second depth of layer as a percentage of the substrate thickness **209** can be in a range from about 5% to about 30%, from about 10% to about 25%, from about 10% to about 22%, from about 12% to about 20%, from about 12% to about 17%, from about 15% to about 17%, or any range or subrange therebetween. In aspects, the first depth of layer of the one or more alkali-metal ions and/or the second depth of layer of the one or more alkali-metal ions can be about 1 μm or more, about 10 μm or more, about 15 μm or more, about 20 μm or more, about 25 μm or more, about 30 μm or more, about 200 μm or less, about 150 μm or less, about 100 μm or less, about 60 μm or less, about 45 μm or less, about 30 μm or less, or about 20 μm or less. In aspects, the first depth of layer of the one or more alkali-metal ions and/or the second depth of layer of the one or more alkali-metal ions can be in a range from about 1 μm to about 200 μm, from about 1 μm to about 150 μm, from about 10 μm to about 100 μm, from about 15 μm to about 600 μm, from about 20 μm to about 45 μm, from about 20 μm to about 30 μm, or any range or subrange therebetween.

[0178] In aspects, the first portion **221** may comprise a first tensile stress region. In aspects, the first tensile stress region can be positioned between the first compressive stress region and the second compressive stress region. In aspects, the first tensile stress region can comprise a maximum first tensile stress. In further aspects, the maximum first tensile stress can be about 10 MPa or more, about 20 MPa or more, about 30 MPa or more, about 100 MPa or less, about 80 MPa or less, or about 60 MPa or less. In further aspects, the maximum first tensile stress can be in a range from about 10 MPa to about 100 MPa, from about 10 MPa to about 80 MPa, from about 10 MPa to about 60 MPa, from about 20 MPa to about 100 MPa, from about 20 MPa to about 80 MPa, from about 20 MPa to about 60 MPa, from about 30 MPa to about 100 MPa, from about 30 MPa to about 80 MPa, from about 30 MPa to about 60 MPa, or any range or subrange therebetween. Providing a maximum first tensile stress in a range from about 10 MPa to about 100 MPa can enable good impact and/or puncture resistance while providing low energy fractures, as discussed below.

[0179] In aspects, the second portion **231** comprising a second glass-based and/or ceramic-based portion may comprise a third compressive stress region at the third surface area **233** that can extend to a third depth of compression from the third surface area **233**. In aspects, the second portion **231** comprising a second glass-based and/or ceramic-based portion may comprise a fourth compressive stress region at the fourth surface area **235** that can extend to a fourth depth of compression from the fourth surface area **235**. In aspects, the third depth of compression and/or the fourth depth of compression as a percentage of the substrate thickness **209** can be within one or more of the ranges discussed above for the first depth of compression and/or the second depth of compression. In further aspects, the third depth of compression can be substantially equal to the fourth depth of compression. In aspects, the third depth of compression and/or the fourth depth of compression can be within one or more of the ranges discussed above for the first depth of compression and/or the second depth of compression. By providing a second portion comprising a glass-based and/or ceramic-based portion comprising a third depth of compression and/or a fourth depth of compression in a range from about 1% to about 30% of the substrate thickness, good impact and/or puncture resistance can be enabled.

[0180] In aspects, the third compressive stress region can comprise a maximum third compressive stress. In aspects, the fourth compressive stress region can comprise a maximum fourth compressive stress. In further aspects, the maximum third compressive stress and/or the maximum fourth compressive stress can be within one or more of the ranges discussed above for the maximum first compressive stress and/or the maximum second compressive stress. By providing a maximum third compressive stress and/or a maximum fourth compressive stress in a range from about 100 MPa to about 1,500 MPa, good impact and/or puncture resistance can be enabled.

[0181] In aspects, the second portion **231** can comprise a third depth of layer of one or more alkali-metal ions associated with the third compressive stress region and the third depth of compression. In aspects, the second portion **231** can comprise a fourth depth of layer of one or more alkali-metal ions associated with the fourth compressive stress region and the fourth depth of compression. In aspects, the one or more alkali ions of the third depth of layer of the one or more alkali ions and/or the fourth depth of layer of the one or more alkali ions comprises potassium. In aspects, the third depth of layer and/or the fourth depth of layer as a percentage of the substrate thickness **209** can be within one or more of the ranges discussed above for the first depth of layer and/or the second depth of layer as a percentage of the substrate thickness **209**. In aspects, the third depth of layer of the one or more alkali-metal ions and/or the fourth depth of layer of the one or more alkali-metal ions can be the first depth of layer and/or the second depth of layer.

[0182] In aspects, the second portion **231** may comprise a second tensile stress region. In aspects, the second tensile stress region can be positioned between the third compressive stress region and the fourth compressive stress region. In aspects, the second tensile stress region can comprise a maximum second tensile stress. In further aspects, the maximum second tensile stress can be within one or more of the ranges discussed above for the maximum first tensile stress. In aspects, the maximum first tensile stress can be substantially equal to the maximum second tensile stress. Providing a maximum second tensile stress in a range from about 10 MPa to about 100 MPa can enable good impact and/or puncture resistance while providing low energy fractures, as discussed below.

[0183] In aspects, the first depth of compression can be substantially equal to the third depth of compression. In aspects, the second depth of compression can be substantially equal to the fourth depth of compression. In aspects, the maximum first compressive stress can be substantially equal to the maximum third compressive stress. In aspects, the maximum second compressive stress can be substantially equal to the maximum fourth compressive stress. In aspects, the first depth of layer of one or more alkali-metal ions can be substantially equal to the third depth of layer of one or more alkali-metal ions. In aspects, the second depth of layer of one or more alkali-metal ions can be substantially equal to the fourth depth of layer of one or more alkali-metal ions.

[0184] In aspects, the central portion **281** can have one or more compressive stress regions. In further aspects, there can be a first central compressive stress region extending to a first central depth of compression from the first central surface area **213**, and/or there can be a second central compressive stress region extending to a second central depth of compression from the second central surface area **243**. In further aspects, the first central compressive stress region and/or the second central compressive stress region can be within the central portion **281** (e.g., coextensive with the first central surface area **213** and/or the second central surface area **243**). In further aspects, the first central depth of compression and/or the second central depth of compression as a percentage of the central thickness **289** or the local thickness can be within one or more of the ranges discussed above for the first depth of compression and/or the second depth of compression as a percentage of the substrate thickness **209**. In further aspects, the first central depth of compression and/or the second central depth of compression as a percentage of the central thickness **289** or the local thickness can be about 1% or more, about 2% or more, about 5% or more, about 8% or more, about 10% or more, about 12% or more, about 20% or less, about 17% or less, about 15% or less, about 12% or less, about 10% or less, about 7% or less, or about 5% or less. For example, the first central depth of compression and/or the second central depth of compression as a percentage of the central thickness **289** or the local thickness can be in a range from about 1% to about 20%, from about 2% to about 17%, from about 5% to about 15%, from about 7% to about 10%, or any range or subrange therebetween. In further aspects, the first central depth of compression can be substantially equal to the second central depth of compression. In further aspects, the first central depth of compression and/or the second central depth of compression can be within one or more of the ranges discussed above for the first depth of compression and/or the second depth of compression. In further aspects, the first central depth of compression and/or the second central depth of compression can be about 1 μm or more about 2 μm or more, about 4 μm or more, about 6 μm or more, about 20 μm or less, about 15 μm or less, about 10 μm or less, or about 8 μm or less. For example, the first central depth of compression and/or the second central depth of compression can be in a range from about 1 μm to about 20 μm, from about 2 μm to about 15 μm, from about 4 μm to about 10 μm, from about 6 μm to about 8 μm, or any range or subrange therebetween. By providing a central portion comprising a glass-based and/or ceramic-based portion comprising a first central depth of compression and/or a second central depth of compression in a range from about 1% to about 30% (e.g., from about 1% to about 20%) of the central thickness or local thickness, good impact and/or puncture resistance can be enabled.

[0185] In aspects, the first central compressive stress region can comprise a maximum first central compressive stress. In aspects, the second central compressive stress region can comprise a maximum second central compressive stress. In further aspects, the maximum first central compressive stress and/or the maximum second central compressive stress can be within one or more of the ranges discussed above for the maximum first compressive stress and/or the maximum second compressive stress. By providing a maximum first central compressive stress and/or a maximum second central compressive stress in a range from about 100 MPa to about 1,500 MPa, good impact and/or puncture resistance can be enabled.

[0186] In aspects, the central portion **281** can comprise a first central depth of layer of one or more alkali-metal ions associated with the first central compressive stress region and the first central depth of compression. In aspects, the central portion **281** can comprise a second central depth of layer of one or more alkali-metal ions associated with the second central compressive stress region and the second central depth of compression. In aspects, the one or more alkali ions of the first central depth of layer of the one or more alkali ions and/or the second central depth of layer of the one or more alkali ions comprises potassium. In aspects, the first central depth of layer and/or the second central depth of layer as a percentage of the central thickness **289** or the local thickness can be within one or more of the ranges discussed above for the first depth of layer and/or the second depth of layer as a percentage of the substrate thickness **209**.

[0187] In aspects, the first central depth of layer and/or the second central depth of layer as a percentage of the central thickness **289** or the local thickness can be about 1% or more, about 2% or more, about 5% or more, about 8% or more, about 10% or more, about 12% or more, about 20% or less, about 17% or less, about 15% or less, about 12% or less, about 10% or less, about 7% or less, or about 5% or less. For example, the first central depth of layer and/or the second central depth of layer as a percentage of the central thickness **289** or the local thickness can be in a range from about 1% to about 20%, from about 2% to about 17%, from about 5% to about 15%, from about 7% to about 10%, or any range or subrange therebetween. In further aspects, the first central depth of layer can be substantially equal to the second central depth of layer. In further aspects, the first central depth of layer and/or the second central depth of layer can be within one or more of the ranges discussed above for the first depth of layer and/or the second depth of layer. In further aspects, the first central depth of layer and/or the second central depth of layer can be about 1 μm or more about 2 μm or more, about 4 μm or more, about 6 μm or more, about 20 μm or less, about 15 μm or less, about 10 μm or less, or about 8 μm or less. For example, the first central depth of layer and/or the second central depth of layer can be in a range from about 1 μm to about 20 μm, from about 2 μm to about 15 μm, from about 4 μm to about 10 μm, from about 6 μm to about 8 μm, or any range or subrange therebetween.

[0188] In aspects, the central portion **281** may comprise a central tensile stress region. In aspects, the central tensile stress region can be positioned between the first central compressive stress region and the second central compressive stress region. In aspects, the central tensile stress region can comprise a maximum central tensile stress. In further aspects, the maximum central tensile stress can be about 125 MPa or more, about 150 MPa or more, about 200 MPa or more, about 375 MPa or less, about 300 MPa or less, or about 250 MPa or less. In further aspects, the maximum central tensile stress can be in a range from about 125 MPa to about 375 MPa, from about 125 MPa to about 300 MPa, from about 125 MPa to about 250 MPa, from about 150 MPa to about 375 MPa, from about 150 MPa to about 300 MPa, from about 150 MPa to about 250 MPa, from about 200 MPa to about 375 MPa, from about 200 MPa to about 300 MPa, from about 200 MPa to about 250 MPa, or any range or subrange therebetween. Providing a maximum central tensile stress in a range from about 125 MPa to about 375 MPa can enable low minimum bend radii.

[0189] In aspects, one or more of the protrusions of the plurality of protrusions can be chemically strengthened with a corresponding compressive stress region extending to a corresponding depth of compression from the corresponding outer surface (e.g., upper surface). In further aspects, all of the protrusions of the plurality of protrusions can be chemically strengthened with a corresponding compressive stress region extending to a corresponding depth of compression from the corresponding outer surface (e.g., upper surface). In further aspects, the maximum compressive stress of a compressive stress region of at least one of the protrusions of the plurality of protrusions can be in one or more of the ranges discussed above for the maximum first central compressive stress and/or the maximum first central compressive stress. In even further aspects, the maximum compressive stress of a compressive stress region of at least one of the protrusions of the plurality of protrusions can be substantially equal to and/or within 100 MPa of the maximum first central compressive stress and/or the maximum first central compressive stress. In further aspects, the depth of compression of a compressive stress region of at least one of the protrusions of the plurality of protrusions can be in one or more of the ranges discussed above for the first depth of compression and/or the first central depth of compression as a percentage of the corresponding thickness and/or in absolute units. In further aspects, a depth of layer of one or more alkali metal ions (e.g., potassium) associated with the compressive stress region of at least one of the protrusions of the plurality of protrusions can be in one or more of the ranges discussed above with reference to the first depth of layer and/or the first central depth of layer. In even further aspects, a depth of layer of one or more alkali metal ions (e.g., potassium) associated with the compressive stress region of at least one of the protrusions of the plurality of protrusions can be substantially equal to the first depth of layer and/or the first central depth of layer. For example, in accordance with some of the methods discussed below involving simultaneously exposing the first major surface, the first central surface area, and the plurality of protrusions to a molten salt bath, compressive stress regions can be developed simultaneously associated depth of layer (in absolute units—μm) being substantially the same for all.

[0190] FIG. **7** schematically illustrates aspects of a foldable apparatus **301** in accordance with aspects of the disclosure in a folded configuration. As shown in FIG. **7**, the foldable apparatus **301** is folded such that the first major surface **203** of the foldable substrate **201** is on the inside of the folded foldable apparatus **301**. For example, a display could be located on the side of the second major surface **205**, and a viewer would view the display from the side of the first major surface **203**. Alternatively, a display could be located on the side of the first major surface **203**, and a viewer would view the display from the side of the second major surface **205**. Alternatively, although not shown, the foldable apparatus can be folded such that the second major surface **205** of the foldable substrate **201** is on the inside of the folded foldable apparatus. For example, a display could be located on the side of the second major surface **205**, and a viewer would view the display from the side of the first major surface **203**. Alternatively, a display could be located on the side of the first major surface **203**, and a viewer would view the display from the side of the second major surface **205**.

[0191] As used herein, "foldable" includes complete folding, partial folding, bending, flexing, or multiple capabilities. As used herein, the terms "fail," "failure" and the like refer to breakage, destruction, delamination, or crack propagation. Likewise, a foldable apparatus achieves a parallel plate distance of "X," or has a parallel plate distance of "X," or comprises a parallel plate distance of "X" if it resists failure when the foldable apparatus is held at a parallel plate distance of "X" for 24 hours at about 85° C. and about 85% relative humidity.

[0192] As used herein, the "parallel plate distance" of a foldable apparatus and/or foldable substrate is measured with the following test configuration and process using a parallel plate apparatus **701** (see FIG. **7**) that comprises a pair of parallel rigid stainless-steel plates **703**, **705** comprising a first rigid stainless-steel plate **703** and a second rigid stainless-steel plate **705**. When measuring the "parallel plate distance" for the foldable substrate **201** (e.g., the foldable apparatus **101** and/or **301** shown in FIGS. **2-3** consisting of foldable substrate **201**), as shown in FIG. **7**, the foldable substrate **201** is placed between the pair of plates **703** and **705** such that the second major surface **205** is in contact with the pair of plates **703** and **705**. For determining a "parallel plate distance", the distance between the parallel plates is reduced at a rate of 50 μm/second until the parallel plate distance **711** is equal to the "parallel plate distance" to be tested. Then, the parallel plates are held at the "parallel plate distance" to be tested for 24 hours at about 85° C. and about 85% relative humidity. As used herein, the "minimum parallel plate distance" is the smallest parallel plate distance that the foldable apparatus can withstand without failure under the conditions and configuration described above.

[0193] In aspects, the foldable apparatus **101** and/or **301** and/or foldable substrate **201** can achieve a parallel plate distance of 100 mm or less, 50 mm or less, 20 mm or less, 10 mm or less, 5 mm or less, 4 mm or less, 3 mm or less, 2 mm or less, or 1 mm or less. In further aspects, the foldable apparatus **101** and/or **301** and/or foldable substrate **201** can achieve a parallel plate distance of 50 millimeters (mm), or 20 mm, or 10 mm, 8 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, or 1 mm. In aspects, the foldable apparatus **101** and/or **301** and/or foldable substrate **201** can comprise a minimum parallel plate distance of about 40 mm or less, about 20 mm or less, about 10 mm or less, about 8 mm or less, about 6 mm or less, about 5 mm or less, about 4 mm or less, about 3 mm or less, about 2 mm or less, about 1 mm or less, about 1 mm or more, about 2 mm or more, about 3 mm or more, about 4 mm or more, about 5 mm or more, or about 10 mm or more. In aspects, the foldable apparatus **101** and/or **301** and/or foldable substrate **201** can comprise a minimum parallel plate distance in a range from about 1 mm to about 40 mm, from about 1 mm to about 20 mm, from about 1 mm to about 10 mm, from about 1 mm to about 5 mm, from about 2 mm to about 3 mm, or any range or subrange therebetween. In aspects, the foldable apparatus **101** and/or **301** and/or foldable substrate **201** can achieve a minimum parallel plate distance in a range from about 2 mm to about 40 mm, from about 2 mm to about 20 mm, from about 2 mm to about 10 mm, from about 3 mm to about 10 mm, from about 3 mm to about 8 mm, from about 3 mm to about 6 mm, from about 4 mm to about 5 mm, or any range or subrange therebetween.

[0194] In aspects, the central width **287** of the central portion **281** of the foldable substrate **201** can be about 1.3 times or more, about 1.6 times or more, about 1.8 times or more, about 2 times or more, about 2.2 times or more, about 3 times or less, about 2.5 times or less, about 2 times or less, about 1.8 times or less, or about 1.5 times or less the minimum parallel plate distance. In aspects, the central width **287** of central portion **281** of the foldable substrate **201** as a multiple of the minimum parallel plate distance can be in a range from about 1.3 times to about 3 times, from about 1.6 times to about 2.5 times, from about 1.8 times to about 2.2 times, from about 2 times to about 2.2 times, or any range or subrange therebetween. Without wishing to be bound by theory, the length of a bend portion in an elliptical configuration between parallel plates can be about 2.2 times the parallel plate distance **711**. In aspects, the central width **287** of the central portion **281** of the foldable substrate **201** can be about 1 mm or more, about 3 mm or more, about 5 mm or more, about 6 mm or more, about 8 mm or more, about 10 mm or more, about 15 mm or more, about 20 mm or more, about 100 mm or less, about 60 mm or less, about 50 mm or less, about 40 mm or less, about 35 mm or less, about 30 mm or less, about 25 mm or less, about 20 mm or less, about 15 mm or less, or about 10 mm or less. In aspects, the central width **287** of central portion **281** of the foldable substrate **201** can be in a range from about 1 mm to about 100 mm, from about 2 mm to about 60 mm, from about 3 mm to about 50 mm, from about 5 mm to about 40 mm, from about 6 mm to about 35 mm, from about 6 mm to about 30 mm, from about 8 mm to about 25 mm, from about 8 mm to about 20 mm, from about 10 mm to about 15 mm, or any range of subrange therebetween. In aspects, the central width **287** of the central portion **281** of the foldable substrate **201** can be in a range from about 2.8 mm to about 60 mm, from about 2.8 mm to about 40 mm, from about 2.8 mm to about 24 mm, from about 6 mm to about 60 mm, from about 6 mm to about 40 mm, from about 6 mm to about 24 mm, from about 9 mm to about 60 mm, from about 9 mm to about 40 mm, from about 9 mm to about 24 mm, or any range of subrange therebetween. By providing a central width within the above-noted ranges in this paragraph, folding of the foldable apparatus without failure can be facilitated.

[0195] In aspects, the central width **287** of the central portion **281** as a percentage of the length **105** of the foldable apparatus can be about 30% or more, about 35% or more, about 40% or more, about 45% or more, about 70% or less, about 60% or less, about 55% or less, or about 50% or less. In aspects, the central width **287** of the central portion **281** as a percentage of the length **105** of the foldable apparatus can range from about 30% to about 70%, from about 35% to about 60%, from about 40% to about 55%, from about 45% to about 50%, or any range or subrange therebetween. In aspects, the central width **287** of the central portion **281** can be about 30 mm or more, about 35 mm or more, about 40 mm or more, about 45 mm or more, about 50 mm or more, about 100 mm or less, about 80 mm or less, about 70 mm or less, or about 60 mm or less. In aspects, the central width **287** of the central portion **281** can range from about 30 mm to about 100 mm, from about 35 mm to about 80 mm, from about 40 mm to about 70 mm, from about 45 mm to about 60 mm, from about 50 mm to about 60 mm, or any range or subrange therebetween.

[0196] In aspects, the foldable substrate and/or the foldable apparatus can be rollable. As used herein, a foldable substrate or a foldable apparatus is "rollable" if it can achieve a threshold parallel plate distance over a length of the corresponding foldable substrate and/or foldable apparatus that is the greater of 10 mm or 10% of the length of the corresponding foldable substrate and/or foldable apparatus. For example, as shown in FIG. **37**, the foldable substrate **201** is considered "rollable" when the central width **287** of the central portion **281** is greater than 10% of the length **105** (see FIG. **1**) extending in the direction **106** of the length **105**.

[0197] A minimum force may be used to achieve a predetermined parallel plate distance with the foldable apparatus and/or foldable substrate. The parallel plate apparatus **701** of FIGS. **7-8**, described above, is used to measure the "bend force" of a foldable apparatus and/or foldable substrate in accordance of the disclosure in the Parallel Plate Test. The force to go from a flat configuration (e.g., see FIGS. **2-3**) to a bent (e.g., folded) configuration (e.g., see FIGS. **7-8**) comprising the predetermined parallel plate distance is measured. In aspects, an bend force comprising the minimum force to bend the foldable apparatus and/or the foldable substrate from a flat configuration to a parallel plate distance of 6 mm (e.g., when a maximum thickness of the foldable substrate is about 70 μm or more) can be about 0.24 Newtons per millimeter width of the foldable substrate (N/mm) or less, about 0.22 N/mm or less, about 0.20 N/mm or less, about 0.18 N/mm or less, about 0.01 N/mm or more, about 0.05 N/mm or more, about 0.10 N/mm or more, or about 0.15 N/mm or more. In aspects, a bend force comprising the minimum force to bend the foldable apparatus and/or the foldable substrate from a flat configuration to a parallel plate distance of 6 mm (e.g., when a maximum thickness of the foldable substrate is about 70 μm or more) can be in a range from about 0.01 N/mm to about 0.24 N/mm, from about 0.05 N/mm to about 0.22 N/mm, from about 0.10 N/mm to about 0.20 N/mm, from about 0.15 N/mm to about 0.18 N/mm, or any range or subrange therebetween. In aspects, a bend force a foldable substrate comprising a thickness profile associated with a first folding surface area in accordance with aspects of the present disclosure with a maximum thickness can be lower than a comparative bend force of a substrate with a uniform thickness equal to the maximum thickness at the same parallel plate distance (e.g., 6 mm) by 20% or more, 25% or more, or 30% or more, for example, in a range from about 20% to about 75%, from about 25% to about 50%, or from about 30% to about 40%, or any range or subrange therebetween.

[0198] As used herein, the "Pen Drop Test" and the "Quasi-Static Puncture Test" uses a multilayer apparatus constructed using the foldable substrate to be tested. An example multilayer apparatus in FIG. **11** comprises the foldable substrate **201** with a test adhesive layer filling the central portion and further comprising a test adhesive thickness of 15 μm that is, in turn, contacting a polymer sheet comprising a thickness of 50 μm. The polymer sheet is low density polyethylene (LDPE) with a thickness of 250 μm. The test adhesive layer comprised an elastic modulus of 0.8 MPa with a tensile strength of about 0.58 MPa and an elongation at failure of about 220%. A first major surface of the second PET sheet (opposite the second major surface) forms an exterior surface of the multilayer apparatus to be tested. Unless otherwise indicated, the additional thickness **249** of the polymer-based portion **261** is 15 μm in the multilayer apparatus for the "Pen Drop Test" and the "Quasi-Static Puncture Test".

[0199] The "Pen Drop Test" is conducted such that the polymer sheet is placed on an aluminum plate (6063 aluminum alloy, as polished to a surface roughness with 400 grit paper) with polymer sheet contacting the aluminum plate. No tape is used on the side of the sample resting on the aluminum plate. The polymer sheet faces the direction of gravity. As described herein, a load (i.e., from a pen dropped from a certain height) is imparted to an outer major surface (e.g., second major surface **205**). A tube is used for the Pen Drop Test to guide a pen to an outer surface of the foldable apparatus. The tube is placed in contact with the second major surface **205** so that the longitudinal axis of the tube is substantially perpendicular to the outer major surface with the longitudinal axis of the tube extending in the direction of gravity.

[0200] Referring to FIG. **11**, a pen drop apparatus **1101** includes a ballpoint pen **1103**, which is a BIC Easy Glide Pen, Fine comprising a tungsten carbide ballpoint tip **1105** of 0.7 mm (0.68 mm) diameter, and a weight of 5.73 grams (g) including the cap. The ballpoint pen **1103** is held at a predetermined height **1109** from an outer surface (e.g., second major surface **205**) of the multilayer apparatus being tested. A tube (not shown for clarity) is used as part of the pen drop apparatus **1101** to guide the ballpoint pen **1103** to the outer surface (e.g., second major surface **205**) of the sample, and the tube is placed in contact with the second major surface **205** so that the longitudinal axis of the tube is substantially perpendicular to the outer major surface with the longitudinal axis of the tube extending in the direction of gravity. The tube has an outside diameter of 1 inch (2.54 cm), an inside diameter of nine-sixteenths of an inch (1.4 cm), and a length of 90 cm. An acrylonitrile butadiene ("ABS") shim (not shown) is employed to hold the ballpoint pen **1103** at a predetermined height **1109** for each test.

[0201] For the Pen Drop Test, the ballpoint pen **1103** is dropped with the cap attached to the top end (i.e., the end opposite the ballpoint tip **1105**) so that the ballpoint tip **1105** can interact with the test sample (e.g., second major surface **205**). In a drop sequence according to the Pen Drop Test, one pen drop is conducted at an initial height of 1 cm, followed by successive drops in 0.5 cm increments up to 20 cm, and then after 20 cm, 2 cm increments until failure of the test sample. After each drop is conducted, the presence of any observable fracture, failure, or other evidence of damage to the sample is recorded along with the particular pen drop height. After each drop, the tube is relocated relative to the outer surface of the sample to be tested to guide the ballpoint pen **1103** to a different impact location on the outer surface of the sample to be tested. The ballpoint pen is changed to a new pen after every 5 drops, and for each new multilayer apparatus tested. In addition, all pen drops are conducted at random locations on the second major surface **205** that are at or near the center of the second major surface **205** unless indicated otherwise, with no pen drops near or on the edge of the sample. Using the Pen Drop Test, multiple samples can be tested according to the same drop sequence to generate a population with improved statistical accuracy.

[0202] For purposes of the Pen Drop Test, "failure" means the formation of a visible mechanical defect in a laminate. The mechanical defect may be a crack or plastic deformation (e.g., surface indentation). The crack may be a surface crack or a through crack. The crack may be formed on an interior or exterior surface of a laminate. The crack may extend through all or a portion of the foldable substrate **201** and/or coating. A visible mechanical defect has a minimum dimension of 0.2 mm or more.

[0203] In aspects, the foldable apparatus can resist failure for a pen drop in a region comprising the first portion **221** or the second portion **231** at a pen drop height of 10 centimeters (cm), 12 cm, 14 cm, 16 cm, or 20 cm. In aspects, a maximum pen drop height that the foldable apparatus can withstand without failure over a region comprising the first portion **221** or the second portion **231** may be about 10 cm or more, about 12 cm or more, about 14 cm or more, about 16 cm or more, about 40 cm or less, or about 30 cm or less, about 20 cm or less, about 18 cm or less. In aspects, a maximum pen drop height that the foldable apparatus can withstand without failure over a region comprising the first portion **221** or the second portion **231** can be in a range from about 10 cm to about 40 cm, from about 12 cm to about 40 cm, from about 12 cm to about 30 cm, from about 14 cm to about 30 cm, from about 14 cm to about 20 cm, from about 16 cm to about 20 cm, from about 18 cm to about 20 cm, or any range or subrange therebetween.

[0204] In aspects, the foldable apparatus can resist failure for a pen drop in the central portion **281** (e.g., between the first portion **221** and the second portion **231**, comprising the plurality of protrusions **251** or **351**) at a pen drop height of 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, or more. In aspects, a maximum pen drop height that the foldable apparatus can withstand without failure over the central portion **281** (e.g., between the first portion **221** and the second portion **231**) may be about 1 cm or more, about 2 cm or more, about 3 cm or more, about 4 cm or more, about 20 cm or less, about 10 cm or less, about 8 cm or less, or about 6 cm or less. In aspects, a maximum pen drop height that the foldable apparatus can withstand without failure over the central portion **281** (e.g., between the first portion **221** and the second portion **231**) can be in a range from about 1 cm to about 20 cm, from about 2 cm to about 20 cm, from about 2 cm to about 10 cm, from about 3 cm to about 10 cm, from about 3 cm to about 8 cm, from about 4 cm to about 8 cm, from about 4 cm to about 6 cm, or any range or subrange therebetween. In aspects, a maximum pen drop height that the foldable apparatus can withstand without failure of the central portion **281** (e.g., between the first portion **221** and the second portion **231**) can be in a range from about 1 cm to about 10 cm, from about 1 cm to about 8 cm, from about 1 cm to about 5 cm, from about 2 cm to about 5 cm, from about 3 cm to about 5 cm, from about 4 cm to about 5 cm, or any range or subrange therebetween.

[0205] In the Quasi-Static Puncture Test, a tungsten carbide ball with a predetermined diameter is placed on the outer surface (e.g., second major surface **205**) and pressed into the outer surface at a rate of 0.5 mm/min until failure. The multilayer apparatus to be tested is configured such that the polymer sheet is placed on an aluminum plate (6063 aluminum alloy, as polished to a surface roughness with 400 grit paper) with the polymer sheet. No tape is used on the side of the sample resting on the aluminum plate. Unless otherwise indicated, the predetermined diameter of the tungsten carbide ball is 0.5 mm. The foldable substrate and/or foldable apparatus can exhibit a puncture resistance as measured in a Quasi-Static Puncture Test of 2.0 kgf or more, 2.5 kgf or more, 3.0 kgf or more, 3.5 kgf or more, 4.0 kgf or more, 4.2 kgf or more, 4.4 kgf or more, 4.5 kgf or more, 4.6 kgf or more, 4.7 kgf or more, 4.8 kgf or more, 4.9 kgf or more, 5.0 kgf or more.

[0206] As used herein, a "reference substrate" refers to a substrate with a monolithic (in contrast with the foldable substrates in accordance with the present disclosure. The reference substrate comprises the same material as the foldable substrate being compared to it. The reference substrate exhibits a reference minimum parallel plate distance and a reference impact resistance. In aspects, for a reference substrate (having a monolithic thickness) with a reference minimum parallel plate distance equal to the minimum parallel plate distance of the foldable substrate (as measured in a Parallel Plate Test), an impact resistance (as measured in a Quasi-Static Puncture Test with a 0.5 mm diameter tungsten carbide ball) of the foldable substrate can be greater than the reference impact resistance (e.g., by 0.1 kgf or more, by 0.2 kgf or more, by 0.5 kgf or more, from 0.1 kgf to 2 kgf, from 0.2 kgf to 1 kgf, from 0.5 kgf to 0.8 kgf) having a reference minimum parallel plate distance equal to the minimum parallel plate distance of the foldable substrate. In aspects, a "predicted impact resistance" and a "predicted minimum parallel plate distance" can be determined from a calibration curve from a series of reference substrates with various monolithic thicknesses, where the impact resistance and minimum parallel plate distance has been measured. In further aspects, a foldable substrate with a minimum parallel plate distance (as measured in a Parallel Plate Test) can have a greater impact resistance (as measured in a Quasi-Static Puncture Test with a 0.5 mm diameter tungsten carbide ball) than a "predicted impact resistance" associated with a "predicted minimum parallel plate distance," where the reference minimum parallel plate distance is equal to the minimum parallel plate distance of the foldable substrate. For example, as discussed below with reference to FIG. **24**, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness with the same parallel plate distance (e.g., minimum parallel plate distance) (where the parallel plate distance and impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance without negatively impacting foldability (e.g., parallel plate distance). The identified area ratios with the unexpected improvement in impact resistance are discussed above, for example, from 0.10 to 0.70, from 0.20 to 0.60, or from 0.25 to 0.50.

[0207] Throughout the disclosure, a "weighted average thickness" TWA of the central portion of the foldable substrate is defined as TWA=(1−AR)*TC+AR*TP, where AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions. For example, with reference to FIG. **2**, the weight average thickness TWA is calculated based on combined protrusion thickness TP equal to the sum of the central thickness **289** and the protrusion height **259** weighted by the area ratio as a decimal (the total protrusion area divided by the total central area, as discussed above) and the central thickness **289** TC times the quantity 1 minus the area ratio as a decimal. If the central thickness TC is 50 μm, the protrusion thickness is 80 μm (combined protrusion thickness of 50 μm+80 μm=130 μm), and an area ratio of 30%, then the weight average thickness TWA=(1−0.30)*50 μm+0.30*130 μm=74 μm. In aspects, an impact resistance (as measured in a Quasi-Static Puncture Test with a 0.5 mm diameter tungsten carbide ball) of the foldable substrate can be greater than the reference impact resistance (e.g., by 0.1 kgf or more, by 0.2 kgf or more, by 0.5 kgf or more, from 0.1 kgf to 2 kgf, from 0.2 kgf to 1 kgf, from 0.5 kgf to 0.8 kgf) having a monolithic thickness equal to the weighted average thickness of the central portion of the foldable substrate. As discussed above, a "predicted impact resistance" can be determined from a calibration curve from a series of reference substrates with various monolithic thicknesses, where the impact resistance has been measured. In further aspects, a foldable substrate with a weighted average thickness of the central can have a greater impact resistance (as measured in a Quasi-Static Puncture Test with a 0.5 mm diameter tungsten carbide ball) than a "predicted impact resistance" associated with a monolithic thickness equal to the weighted average thickness of the central portion of the foldable substrate. For example, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness equal to a weighted average thickness (defined below) (where the impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance beyond what would be achieved for a substrate with the same weighted average thickness. The identified area ratios with the unexpected improvement in impact resistance are discussed above, for example, from 0.10 to 0.70, from 0.20 to 0.60, or from 0.25 to 0.50. Although not shown, the weighted average thickness can be calculated (as discussed herein) and plotted (similar to FIG. **23** but where the foldable substrates are plotted based on the weighted average thickness rather than the thickness of a monolithic substrate with a corresponding parallel plate distance), and it is contemplated that the points within the area ratios discussed herein (e.g., from 0.10 to 0.70, from 0.20 to 0.60, or from 0.25 to 0.50) will be above a calibration curve for reference samples.

[0208] In aspects, as shown in FIG. **2**, the foldable apparatus **101** can further comprise a polymer-based portion **261** disposed over at least the first central surface area **213**. In further aspects, as shown, the polymer-based portion **261** can be at least partially positioned in a recess **211** defined between the first central surface area **213** and the first plane **204***a* defined by the first major surface **203**. In even further aspects, as shown, the polymer-based portion **261** can further extend beyond the recess **211** and be disposed over the first major surface **203** (e.g., first surface area **223** and/or third surface area **233**) in addition to being disposed over the first central surface area **213**. For example, as shown, the polymer-based portion **261** can completely cover the plurality of protrusions **251** and/or contact the entire outer surface **255***a*-**255***c* of the plurality of protrusions **251**, although space may be provided for an electronic device(s) and/or mechanical device(s) in the recess **211**. Alternatively, although not shown, the polymer-based portion **261** can be positioned entirely within the recess **211** (e.g., not extending beyond the first plane **204***a*).

[0209] In further aspects, as shown in FIG. **2**, the polymer-based portion can comprise a first surface area **283** and a second contact surface **285** opposite the first surface area **283**. In further aspects, as shown, the second contact surface **285** can face and/or contact the first central surface area **213**. In further aspects, as shown, the second contact surface **285** can contact the outer surface **255***a*-**255***c* of one or more protrusions **253***a*-**253***c* of the plurality of protrusions **251**. In further aspects, as shown in FIG. **2**, the first surface area **283** can face and/or contact the release liner **271** (e.g., fourth surface area **275**) (described below) or other material (e.g., display device, another substrate).

[0210] In aspects, as shown in FIG. **2**, an additional thickness **249** of the polymer-based portion **261** is defined between the first major surface **203** (e.g., first plane **204***a*) and the first surface area **283** of the polymer-based portion **261** as an average distance therebetween. In further aspects, as shown, the additional thickness **249** of the polymer-based portion **261** (e.g., extending beyond the recess **211**—extending beyond the first plane **204***a*) can be about 1 μm or more, about 5 μm or more, about 10 μm or more, about 100 μm or less, about 60 μm or less, about 30 μm or less, or about 20 μm or less. In aspects, the additional thickness **249** can be in a range from about 1 μm to about 100 μm, from about 5 μm to about 100 μm, from about 5 μm to about 60 μm, from about 5 μm to about 30 μm, from about 10 μm to about 30 μm, from about 10 μm to about 20 μm, or any range or subrange therebetween. Alternatively, the region occupied by the polymer-based portion **261** in FIG. **2** may, in other aspects, be occupied by more than one polymer-based portion, for example, a stiffer polymer-based portion positioned in the recess **211** and another, less stiff optically-clear and/or pressure sensitive adhesive comprising the additional thickness **249**.

[0211] In aspects, the polymer-based portion **261** can comprise an optically transparent polymer. In aspects, the polymer-based portion **261** can comprise one or more of a polyolefin, a polyamide, a halide-containing polymer (e.g., polyvinylchloride or a fluorine-containing polymer), an elastomer, a urethane, phenolic resin, parylene, polyethylene terephthalate (PET), polyether ether ketone (PEEK), an acrylic (e.g., polymethylmethacrylate (PMMA)), an epoxy, and/or a silicone. Example aspects of polyolefins include low molecular weight polyethylene (LDPE), high molecular weight polyethylene (HDPE), ultrahigh molecular weight polyethylene (UHMWPE), and polypropylene (PP). Example aspects of fluorine-containing polymers include polytetrafluoroethylene (PTFE), polyvinylfluoride (PVF), polyvinylidene fluoride (PVDF), perfluoropolyether (PFPE), perfluorosulfonic acid (PFSA), a perfluoroalkoxy (PFA), fluorinated ethylene propylene (FEP) polymers, and ethylene tetrafluoro ethylene (ETFE) polymers. Example aspects of elastomers include rubbers (e.g., polybutadiene, polyisoprene, chloroprene rubber, butyl rubber, nitrile rubber) and block copolymers (e.g., styrene-butadiene, high-impact polystyrene, poly(dichlorophosphazene). Examples of epoxies include bisphenol-based epoxy resins, novolac-based epoxies, cycloaliphatic-based epoxies, and glycidylamine-based epoxies. Example aspects of polyolefins include low molecular weight polyethylene (LDPE), high molecular weight polyethylene (HDPE), ultrahigh molecular weight polyethylene (UHMWPE), and polypropylene (PP). Example aspects of fluorine-containing polymers include polytetrafluoroethylene (PTFE), polyvinylfluoride (PVF), polyvinylidene fluoride (PVDF), perfluoropolyether (PFPE), perfluorosulfonic acid (PFSA), a perfluoroalkoxy (PFA), fluorinated ethylene propylene (FEP) polymers, and ethylene tetrafluoro ethylene (ETFE) polymers. In further aspects, the polymer-based portion **261** can comprise an optically clear adhesive. In even further aspects, the optically clear adhesive can comprise one or more optically transparent polymers: an acrylic (e.g., polymethylmethacrylate (PMMA)), an epoxy, silicone, and/or a polyurethane. Examples of epoxies include bisphenol-based epoxy resins, novolac-based epoxies, cycloaliphatic-based epoxies, and glycidylamine-based epoxies. In even further aspects, the optically clear adhesive can comprise, but is not limited to, acrylic adhesives, for example, 3M 8212 adhesive, or an optically transparent liquid adhesive, for example, a LOCTITE optically transparent liquid adhesive. Exemplary aspects of optically clear adhesives comprise transparent acrylics, epoxies, silicones, and polyurethanes. For example, the optically transparent liquid adhesive could comprise one or more of LOCTITE AD 8650, LOCTITE AA 3922, LOCTITE EA E-05MR, LOCTITE UK U-09LV, which are all available from Henkel.

[0212] In aspects, the polymer-based portion **261** can comprise an elastic modulus of about 0.001 MegaPascals (MPa) or more, about 0.01 MPa or more, about 0.1 MPa or more, about 1 MPa or less, about 0.5 MPa or less, about 0.1 MPa or less, or about 0.05 MPa or less. In aspects, the polymer-based portion **261** can comprise an elastic modulus in a range from about 0.001 MPa to about 1 MPa, from about 0.01 MPa to about 1 MPa, from about 0.01 MPa to about 0.5 MPa, from about 0.05 MPa to about 0.5 MPa, from about 0.1 MPa to about 0.5 MPa, from about 0.001 MPa to about 0.5 MPa, from about 0.001 MPa to about 0.01 MPa, or any range or subrange therebetween. Alternatively, the polymer-based portion **261** can comprise an elastic modulus of about 1 MPa or more, about 10 MPa or more, about 20 MPa or more, about 100 MPa or more, about 200 MPa or more, about 1,000 MPa or more, about 5,000 MPa or less, about 3,000 MPa or less, about 1,000 MPa or less, about 500 MPa or less, or about 200 MPa or less. In aspects, the polymer-based portion **261** can comprise an elastic modulus in a range from about 1 MPa to about 5,000 MPa, from about 1 MPa to about 3,000 MPa, from about 10 MPa to about 1,000 MPa, from about 10 MPa to about 500 MPa, from about 20 MPa to about 200 MPa, from about 20 MPa to about 200 MPa, from about 100 MPa to about 200 MPa, or any range or subrange therebetween.

[0213] In aspects, as shown in FIG. **2**, the foldable apparatus **101** can comprise the release liner **271** although other substrates (e.g., glass-based substrate and/or ceramic-based substrate discussed throughout the application) may be used in further aspects rather than the illustrated release liner **271**. In further aspects, as shown in FIG. **2**, the release liner **271**, or another substrate, can be disposed over the polymer-based portion **261**. In even further aspects, as shown, the release liner **271**, or another substrate, can directly contact the first surface area **283** of the polymer-based portion **261**. The release liner **271**, or another substrate, can comprise a third surface area **273** and a fourth surface area **275** opposite the third surface area **273**. As shown, the release liner **271**, or another substrate, can be disposed on the polymer-based portion **261** by attaching the first surface area **283** of the polymer-based portion **261** to the fourth surface area **275** of the release liner **271**, or another substrate. In aspects, as shown, the third surface area **273** of the release liner **271**, or another substrate, can comprise a planar surface. In aspects, as shown, the fourth surface area **275** of the release liner **271**, or another substrate, can comprise a planar surface. A substrate comprising the release liner **271** can comprise a paper and/or a polymer. Exemplary aspects of paper comprise kraft paper, machine-finished paper, poly-coated paper (e.g., polymer-coated, glassine paper, siliconized paper), or clay-coated paper. Exemplary aspects of polymers comprise polyesters (e.g., polyethylene terephthalate (PET)) and polyolefins (e.g., low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP)). The release liner **271** can be replaced with a display device, a touch sensor, a polymer-based substrate, a glass-based substrate, and/or a ceramic-based substrate.

[0214] Aspects of making foldable substrates of the present disclosure will now be discussed with reference to the flow chart in FIG. **12** and exemplary steps shown in FIGS. **13-21**. In aspects, the foldable apparatus **101** and/or **301** shown in FIGS. **2-7** can be formed by applying a patterned etch mask with the location and length of portions of the patterned etch mask being proportional to the width of the corresponding protrusions of the plurality of protrusions in the resulting foldable substrate to form a masked surface. Then, the masked surface can be etched (e.g., using a mineral acid, using a plasma dry etching) to form the first central surface area with associated recesses defining the plurality of protrusions.

[0215] Methods can start at step **1201** comprising providing an initial substrate (e.g., monolithic substrate), which can be provided by purchase or otherwise obtaining a substrate or by forming the foldable substrate. In aspects, the initial substrate can comprise a glass-based substrate and/or a ceramic-based substrate. In further aspects, glass-based substrates and/or ceramic-based substrates can be provided by forming them with a variety of ribbon forming processes, for example, slot draw, down-draw, fusion down-draw, up-draw, press roll, redraw, or float. In further aspects, ceramic-based substrates can be provided by heating a glass-based substrate to crystallize one or more ceramic crystals. In aspects, although not shown, at the end of step **1201**, the initial substrate can comprise an initial central thickness less than the initial thickness, for example, with the initial central thickness substantially equal to the combined protrusion thickness (i.e., the sum of the resulting central thickness and the protrusion height). In further aspects, the initial central thickness can be formed by etching the central portion (e.g., uniformly) without etching the first portion and the second portion. In aspects, as shown in FIG. **13**, at the end of step **1201**, an etch mask **1311** having one or more portions **1313***a*, **1313***b*, and/or **1317** can be disposed over an initial first major surface **1303** in a first portion **1321**, the initial first major surface **1303** in a second portion **1331**, and/or an initial second major surface **1305** (e.g., opposite the initial first major surface **1303** with an initial thickness **1309** defined therebetween), although the etch mask may be deposited in subsequent steps (e.g., step **1203**).

[0216] In aspects, after step **1201**, methods can (follow arrow **1206**) to proceed to step **1215** comprising disposing a patterned mask (e.g., etch mask **1311** have portions **1413***c*-**1413***e*) on at least an initial central surface area **1313** in a central portion **1381** of the initial substrate **1301**, as shown in FIG. **14**. As shown, the patterned mask (e.g., etch mask **1311**) includes a plurality of separate sections (e.g., portions **1413***c*-**1413***e*). For example, as shown, portions **1413***c*-**1413***e* of the patterned mask (e.g., etch mask **1311**) can be disposed over and/or disposed on the initial central surface area **1313**. These portions **1413***c*-**1413***e* can be disposed using a common method with other portions of the etch mask **1311** (e.g., portions **1313***a*-**1313***b* of the patterned mask in FIGS. **13-14** and/or portion **1317** shown in FIG. **13**). An arrangement of the plurality of portions **1413***c*-**1413***e* can correspond to an arrangement of protrusions of the plurality of protrusions to be formed (e.g., with a location of the portion corresponding to a location of the protrusion) with the understanding that the width of the protrusions will be the same or less than the width of the corresponding portions of the patterned mask, for example, depending on how the protrusions are formed (e.g., etching conditions). In aspects, as shown in FIG. **14**, material **1405** for the portions **1413***c*-**1413***e* can be dispensed from a container **1401** (e.g., conduit, flexible tube, micropipette, or syringe) onto the initial central surface area **1313**. An exemplary aspect of forming the portions **1413***c*-**1413***e* includes ink-jet deposition (e.g., ink-jet printing). For example, as shown in FIG. **14**, material **1405** corresponding to an "ink" precursor of the portion **1413***c*-**1413***e* can be dispensed from a container **1401** corresponding to a nozzle of an ink-jet printer head, where the material **1405** is dispensed a predetermined locations to form the portions **1413***c*-**1413***e* of the patterned mask (e.g., etch mask **1311**). In aspects, portions **1313***a*-**1313***b* disposed over the first portion **1321** and/or the second portion **1331** can also be formed by ink-jet deposition (e.g., ink-jet printing), although the portions **1313***a*-**1313***b* can be formed by other methods and/or prior to disposing the patterned mask (e.g., portions **1413***c*-**1413***e*). As discussed below with reference to FIGS. **16-19**, the portions of the patterned mask (e.g., etch mask) can be arranged in a row and/or a two-dimensional array, where portions in adjacent columns can be aligned of offset from one another.

[0217] Alternatively, after step **1201**, methods can proceed to step **1203** comprising disposing an etch mask (e.g., portions **1313***a*-**131***b* of the etch mask **1311**) over the first portion **1321** and/or the second portion **1331** of the initial substrate **1301**, as shown in FIG. **13**. In aspects, as shown, portion **1313***a* can be disposed over the and/or disposed on an entirety of the initial first major surface **1303** in the first portion **1321**, and/or portion **1313***b* can be disposed over the and/or disposed on an entirety of the initial first major surface **1303** in the second portion **1331**. Similarly, portion **1317** can be disposed over and/or disposed on the initial second major surface **1305** (e.g., entirety of the initial second major surface **1305**). In aspects, the portions **1313***a*-**1313***b* and/or **1317** can be disposed using a doctor blade method, slot draw coating, spin-coating, or other methods known in the art.

[0218] In aspects, as shown in FIG. **13**, dashed line **1315** indicates the etch mask **1311** can initially cover the initial central surface area **1313**. For example, the entirety of both major surfaces of the initial substrate can be initially coated with the etch mask, which can take advantage of cost-effective deposition methods. In further aspects, the central portion of the etch mask (see region defined by dashed line **1315**) can be removed, for example, if methods are to follow arrow **1208** to step **1215**. Alternatively, in further aspects, the central portion of the etch mask (see region defined by dashed line **1315**) can be selectively removed in subsequent processing (e.g., step **1205**) to form the patterned mask in the central portion (e.g., disposed over and/or disposed on the initial central surface area **1313** as shown in FIG. **15**).

[0219] In aspects, after step **1203**, methods can proceed to step **1205** comprising forming a patterned mask (e.g., etch mask **1311**), for example, by selectively removing portions of the etch mask in the central portion, as shown in FIG. **15**. In further aspects, as shown, a laser beam **1503** can be emitted from a laser **1501**, where the laser beam **1503** impinges a portion of the etch mask **1311** to divide an existing portion (e.g., portion **1313***e*) into new portions **1513***d* and **1313***e* and/or remove material to define a predetermined shape of portion(s) of the patterned mask (e.g., with material of the mask being removed to define the dimensions of portion **1513***c*). Alternatively, although not shown, the patterned mask can be formed using photolithography. For example, predetermined portions of the initial etch mask can be exposed to light and developed (e.g., exposed to a solution) to remove the predetermined portions leaving behind the patterned mask.

[0220] At the end of step **1205** or **1215**, the patterned mask (e.g., etch mask **1311**) can appear as shown in any of FIGS. **16-17**. In aspects, as shown in FIG. **16**, a portion **1313***a* of the etch mask **1311** can be disposed over and/or disposed on the first portion of the initial substrate, a portion **1313***b* of the etch mask **1311** can be disposed over and/or disposed on the second portion of the initial substrate, and the patterned mask **1603** of the etch mask **1311** disposed over and/or disposed on the central portion of the initial substrate. In further aspects, as shown, the patterned mask **1603** may not extend for the full extent of a corresponding dimension of the initial substrate, for example, excluding end portions **1605** or **1607**. In even further aspects, the end portions **1605** or **1607** can be non-patterned portions of the mask or end portions **1605** or **1607** can expose corresponding portions of the initial substrate, although the patterned mask may extend over an entirety of the central portion of the initial substrate in other aspects.

[0221] In aspects, as shown in FIGS. **16-18**, the patterned mask **1603** (FIG. **16**) can comprise a plurality of portions (e.g., portions **1513***c*-**1513***e* in FIG. **17** and/or portions **1513***c*-**1513***e*, **1513***g*-**1513***i*, and/or **1513***k*-**1513***m* in FIGS. **18-19**) that are physically separated from one another. In aspects, as shown in FIGS. **16-17**, the patterned mask can be aligned in a row extending in the direction **106**. In further aspects, as shown, the plurality of protrusions can be arranged in a single row (e.g., one-dimensional row). In further aspects, a length **421** of one or more of the protrusions **253***a*-**253***c* in a direction **104** (perpendicular to the direction **106**), as a percentage of the width **103** of the foldable substrate **201** can be within one or more of the ranges discussed above with reference to FIG. **4** (e.g., from 50% to 100%, from 66% to 99%, from 75% to 98%, from 80% to 95%, from 85% to 92%, from 90% to 92%, or any range or subrange therebetween). As indicated by portions **1605** and **1607** in FIG. **16**, the plurality of protrusions may not extend all the way to the ends (in direction **104**) of the central portion, although the plurality of protrusions can extend for the entire width of the foldable substrate and/or foldable apparatus in the central portion in further aspects. As shown in FIG. **17**, portions of the initial central surface area **1313** (e.g., central portion **1381** of the initial substrate) between the portions (e.g., portions **1513***c* and **1513***d* or portions **1513***d* and **1513***e*). In aspects, an initial gap **1725** or **1727** can be within one or more of the ranges discussed above for the gap width **256***a* of the resulting foldable substrate discussed above with reference to FIG. **4**. In further aspects, the initial gap **1725** or **1727** can be substantially equal to or less than the corresponding gap width of the resulting foldable substrate. In aspects, the initial gap **1725** between a first adjacent pair of portion **1513***c* and **1513***d* can be substantially equal to the initial gap **1727** between a second adjacent pair of portions **1513***d* and **1513***e*, although the initial gap can vary based on distance from a midline (e.g., fold plane). In aspects, a width **1711** or **1713** of a portion **1513***c*-**1513***e* of the patterned mask **1603** can be within one or more of the ranges discussed above for the full width **252***a* and/or upper width **254***a* a protrusion of the resulting foldable substrate discussed above with reference to FIG. **4**. In further aspects, the width **1711** or **1713** can be substantially equal to or greater than the full width **252***a* of a protrusion in the resulting foldable substrate. In further aspects, the width **1711** or **1713** can be greater than the upper width **254***a* of a protrusion in the resulting foldable substrate. In aspects, the width **1711** of a first portion **1513***c* can be substantially equal to the width **1713** of a second portion **1513***d*, although the width can vary based on distance from a midline (e.g., fold plane). In aspects, a location of portions **1513***c*-**1513***e* of the patterned mask **1603** can correspond to a location and/or have a width **1711** or **1713** proportional to a corresponding aspect of protrusions in the resulting foldable substrate.

[0222] In aspects, as shown in FIGS. **18-19**, the portions **1513***c*-**1513***e*, **1513***g*-**1513***i*, and/or **1513***k*-**1513***m* of the patterned mask can arranged in a two-dimensional array with rows extending in the direction **106** and columns extending in the direction **104** (perpendicular to the direction **104**), where adjacent rows and/or columns can be aligned or offset. In aspects, as shown, a column **1811**, **1813**, **1815**, **1911**, **1913**, or **1915** can comprise three or more portions, and/or each row can comprise at least three portions. In aspects, as shown in FIG. **19**, the plurality of portions **1513***c*, **1513***g*, and **1513***k* in a first column **1911** can be aligned with corresponding portions **1513***d*, **1513***h*, and **1513***l* of a second column **1913** of the plurality of columns in the two-dimensional array (e.g., an offset **1841** in FIG. **18** of 0). For example, protrusions in a column **1912**, **1914**, and/or **1916** can be aligned. Alternatively, as shown in FIG. **18**, the plurality of portions **1513***c*, **1513***g*, and **1513***k* in a first column **1811** can be offset from the plurality of portions **1513***d*, **1513***h*, and **1513***l* in a second column **1813** by an offset **1841** that can be within one or more of the ranges discussed above for the offset **531**. In aspects, as shown in FIGS. **18-19**, a portion of the patterned mask comprises a length **1831**, **1833**, **1931**, and/or **1933** that can be within one or more of the ranges discussed above for the upper length **523** and/or **623** of the resulting foldable substrate. In further aspects, the length **1831**, **1833**, **1931**, and/or **1933** can be greater than a corresponding upper length **523** and/or **623** due to undercutting in the etching process of step **1207**. In further aspects, the length **1831**, **1833**, **1931**, and/or **1933** can be greater than or equal to a corresponding full length **521** and/or **613** of the resulting foldable substrate. In aspects, as shown in FIGS. **18-19**, an adjacent pair of portions in the same column (e.g., column **1811**, **1813**, **1815**, **1911**, **1913**, or **1915**) can be separated by a gap length **1835**, **1837**, **1935**, and/or **1937** in the direction **104** that can be within one or more of the ranges discussed above for the gap width **256***a*, **256***b*, **356***a*, and/or **356***b*. As shown in FIGS. **18-19**, an initial gap **1825**, **1827**, **1925**, or **1927** can be within one or more of the ranges discussed above for the gap width **356***a* of the resulting foldable substrate discussed above with reference to FIGS. **5-6**. In further aspects, the initial gap **1825**, **1827**, **1925**, or **1927** can be substantially equal to or less than the corresponding gap width of the resulting foldable substrate. In aspects, a width **1821**, **1823**, **1921**, or **1923** of a portion of the patterned mask can be within one or more of the ranges discussed above for the full width **352***a* and/or upper width **354***a* a protrusion of the resulting foldable substrate discussed above with reference to FIGS. **5-6**. In further aspects, the width **1821**, **1823**, **1921**, or **1923** can be substantially equal to or greater than the full width **352***a* of a protrusion in the resulting foldable substrate. In further aspects, the width **1821**, **1823**, **1921**, or **1923** can be greater than the upper width **354***a* of a protrusion in the resulting foldable substrate. In aspects, the width **1821** or **1921** of a first portion **1513***k* can be substantially equal to the width **1823** or **1923** of a second portion **1513***h*, although the width can vary based on distance from a midline (e.g., fold plane). In aspects, a location of portions **1513***c*-**1513***e*, **1513***g*-**1513***i*, and/or **1513***k*-**1513***m* of the patterned mask can correspond to a location and/or have a width **1821**, **1823**, **1921**, or **1923** proportional to a corresponding aspect of protrusions in the resulting foldable substrate.

[0223] A mask area ratio of the patterned mask **1603** in the central portion **1381** is defined as a total area of portions of the patterned mask **1603** divided by a total surface area of the initial central surface area **1313**. The mask area ratio can be within one or more of the ranges for the area ratio of the resulting foldable substrate discussed above.

[0224] In aspects, after step **1205** or **1215**, methods can proceed to step **1207** comprising etching the initial substrate to form the plurality of protrusions, as shown in FIG. **20**. In aspects, as shown in FIG. **20**, the etching of step **1207** can comprise contacting the initial central surface area **1313** (e.g., central portion **1381**—see FIGS. **14-15**) of the initial substrate **1301** with an etchant **2003** to form the foldable substrate **201**. In further aspects, as shown, the etchant **2003** can be a liquid etchant contained in an etchant bath **2001**. In even further aspects, the etchant can comprise one or more mineral acids (e.g., HCl, HF, H_2SO_4, HNO_3). Without wishing to be bound by theory, the polymer layer can be deflected away from the foldable substrate during etching to enable the etchant access to an additional portion of the foldable substrate that the polymer layer could otherwise be in contact with. While the etchant can contact the additional portion of the foldable substrate by deflection of the polymer layer, diffusion of the etchant to the additional portion is limited, which limits the extent of etching of the additional portion, producing the transition region.

[0225] As shown in FIG. **20**, the etchant **2003** can isotropically etch the exposed portions of the initial central surface area between portions **1313***c*-**1313***f* of the patterned mask to form recesses **2011** (e.g., collectively forming recess **211** in FIG. **2**). Consequently, the etchant can undercut portions of the etch mask by an undercut **2023**. In aspects, the undercut **2023** can be substantially equal to an etched depth **2021** (e.g., corresponding to the first distance **219** in FIG. **2**). Forming the recesses **2011** defines the protrusions (with upper surfaces corresponding to where the substrate contacts the portions **1313***c*-**1313***f* of the patterned mask) forming the foldable substrate **201**. Also, as shown, isotropic etching can form a curved surface, the initial gap **1725**, **1825**, and/or **1925** relative to the undercut **2023** and/or etched depth can determine the extent to which an average slope of the sides of the protrusions appear as rounded (as in FIG. **20**) or more linear and/or angular (as in FIGS. **2-3** and **21**). In aspects, at the end of step **1207** methods can further comprise removing the etch mask (e.g., patterned mask).

[0226] In aspects, after step **1207**, methods can proceed to step **1209** comprising chemically strengthening the foldable substrate **201**, as shown in FIG. **21**. In further aspects, as shown in FIG. **21**, chemically strengthening the foldable substrate **201** can comprise contacting at least a portion of a foldable substrate **201** with a molten salt solution **2103** comprising potassium cations and/or sodium cations in a salt bath **2101**. In further aspects, as shown in FIG. **20**, step **1211** can comprise simultaneously exposing the first major surface **203**, the first central surface area **213**, and the plurality of protrusions **251** to the molten salt solution **2103**. Chemically strengthening a foldable substrate **201** (e.g., glass-based substrate, ceramic-based substrate) by ion exchange can occur when a first cation within a depth of a surface of a foldable substrate **201** is exchanged with a second cation within a molten salt solution **2103** that has a larger radius than the first cation. For example, a lithium cation within the depth of the surface of the foldable substrate **201** can be exchanged with a sodium cation or potassium cation within the molten salt solution **2103**. Consequently, the surface of the foldable substrate **201** is placed in compression and thereby chemically strengthened by the ion exchange process since the lithium cation has a smaller radius than the radius of the exchanged sodium cation or potassium cation within the molten salt solution **2103**. Chemically strengthening the foldable substrate **201** can comprise contacting at least a portion of a foldable substrate **201** comprising lithium cations and/or sodium cations with sodium cations and/or potassium cations of the molten salt solution **2103**. The molten salt solution **2103** can comprise potassium nitrate, potassium phosphate, potassium chloride, potassium sulfate, sodium chloride, sodium sulfate, sodium nitrate, and/or sodium phosphate, whereby lithium cations and/or sodium cations diffuse from the foldable substrate **201** to the molten salt solution **2103** contained in the salt bath **2101**. In aspects, the temperature of the molten salt solution **2103** can be about 300° C. or more, about 360° C. or more, about 400° C. or more, about 500° C. or less, about 460° C. or less, or about 420° C. or less. In aspects, the temperature of the molten salt solution **2103** can be in a range from about 300° C. to about 500° C., from about 360° C. to about 500° C., from about 400° C. to about 500° C., from about 300° C. to about 460° C., from about 360° C. to about 460° C., from about 400° C. to about 460° C., from about 400° C. to about 420° C., from about 300° C. to about 400° C., from about 360° C. to about 420° C., or any range or subrange therebetween. In aspects, the foldable substrate **201** can be in contact with the molten salt solution **2103** for about 5 minutes or more, about 10 minutes or more, about 20 minutes or more, about 30 minutes or more, about 1 hour or more, about 3 hours or more, about 8 hours or less, about 4 hours or less, about 2 hours or less, about 1 hour or less, about 45 minutes or less, or about 20 minutes or less. In aspects, the foldable substrate **201** can be in contact with the molten salt solution **2103** for a time in a range from about 5 minutes to about 8 hours, from about 10 minutes to about 4 hours, from about 20 minutes to about 2 hours, from about 30 minutes to about 1 hour, or any range or subrange therebetween. At the end of step **1211**, the foldable substrate **201** can comprise the compressive stress regions discussed above (e.g., first compressive stress region extending to a first depth of compression from the first major surface in the first portion, second compressive stress region extending to a second depth of compression from the first major surface in the second portion, and/or first central compressive stress region extending to the first central depth of compression from the first central surface area).

[0227] After step **1207** and/or **1209**, methods can proceed to step **1211** comprising assembling a foldable apparatus (e.g., and/or consumer electronic product) using the foldable substrate. For example, a precursor solution can be disposed over the first central surface area (e.g., in the recess) and cured to form a polymer-based portion (e.g., polymer-based portion **261** shown in FIG. **2**). Also, a release liner **271** (see FIG. **2**), display device, or other components can be disposed thereon. Additionally and/or alternatively, a coating (e.g., hard-coating, anti-fingerprint coating) can be disposed on the second major surface **205**.

[0228] After step **1207**, **1209**, or **1211**, methods can proceed to step **1213**, where methods of making the foldable substrate and/or foldable article can be complete. In aspects, methods of making the foldable substrate in accordance with aspects of the disclosure can proceed along steps **1201**, **1203**, **1205**, **1207**, **1209**, **1211**, and **1213** of the flow chart in FIG. **12**, sequentially as discussed above. In aspects, methods can follow arrow **1206** from step **1201** to step **1215**, for example, if the patterned mask is to be formed by disposing material (e.g., ink-jet printing). In aspects, methods can follow arrow **1208** from step **1203** to step **1215**, for example, if the patterned mask in the central portion is to be formed by disposing material (e.g., ink-jet printing) after portions of a mask are formed over the first portion and/or the second portion of the initial substrate. In aspects, methods can follow arrow **1202** from step **1207** to step **1213**, for example, if methods of making the foldable substrate and/or foldable apparatus are complete at the end of step **1213**. In aspects, methods can follow arrow **1204** from step **1209** to step **1213**, for example, if methods of making the foldable substrate and/or foldable apparatus are complete at the end of step **1213**. Any of the above options may be combined to make a foldable apparatus in accordance with the embodiments of the disclosure.

EXAMPLES

[0229] Various aspects will be further clarified by the following examples. Examples comprised glass-based substrates (Composition 1 having a nominal composition in mol % of: 63.6 SiO_2; 15.7 Al_2O_3; 10.8 Na_2O; 6.2 Li_2O; 1.16 ZnO; 0.04 SnO_2; and 2.5 P_2O_5) with dimensions of 100 mm by 160 mm in a direction perpendicular to the substrate thickness. Unless otherwise indicated, the example foldable substrates discussed in this section had a substrate thickness of 130 μm and a central thickness of 80 μm with protrusions extending from the first central surface area for 50 μm (such that the upper surface of the protrusion was coplanar with the first major surface). Reference substrates comprised a monolithic thickness (no recesses or protrusions) with various thicknesses. Parallel plate distances were measured in accordance with the Parallel Plate Test described above, and the impact resistance was measured using the Quasi-Static Puncture Test with a 0.5 mm diameter tungsten carbide ball incident on the central surface area of the substrate (flush with the second major surface).

[0230] Tables 1-2 present properties of the patterned mask and resulting plurality of protrusions in example foldable substrates experimentally fabricated in accordance with aspects of the present disclosure. Table 1 presents the properties for “block” designs (see FIG. **4**) while Table 2 presents the properties of “kerf” designs (see FIG. **5**). For simplicity and to isolate the effect of the plurality of the protrusions, all foldable substrates and reference substrates discussed in this section were not chemically strengthened.

TABLE 1

Properties of Examples 1-16 with the Block Design

Example	1	2	3	4	5	6	8	9	10
Mask Width (mm)	2.0	1.0	0.6	0.45	0.4	0.4	0.4	0.4	0.4
Mask Gap (μm)	60	60	60	60	150	350	600	1200	2200
Protrusion Width (μm)	1860	860	460	310	260	260	260	260	260
Gap Width (μm)	200	200	200	200	290	490	740	1340	2340
Area %	83%	75%	64%	56%	44%	32%	24%	15%	9%

Example	11	12	13	14	15	16
Mask Width (mm)	0.30	0.22	0.22	0.22	0.22	0.22
Mask Gap (row) (μm)	60	60	60	200	500	800
Protrusion Width (μm)	160	80	80	80	80	80
Gap Width (μm)	200	200	200	340	640	940
Area %	52%	41%	26%	18%	10%	7%

TABLE 2

Properties of Examples 16-31 with the Kerf Design (Length 4.75 μm)

Example	17	18	19	20	21	22	23	24	25
Mask Width (mm)	2.0	1.0	0.6	0.45	0.4	0.4	0.4	0.4	0.4
Mask Gap (row) (μm)	60	60	60	60	150	350	600	1200	2200

TABLE 2-continued

Properties of Examples 16-31 with the Kerf Design (Length 4.75 μm)									
Example	17	18	19	20	21	22	23	24	25
Mask Gap (column) (μm)	250	250	250	250	250	250	250	250	250
Protrusion Width (μm)	1860	860	460	310	260	260	260	260	260
Gap Width (row) (μm)	200	200	200	200	290	490	740	1340	2340
Minimum distance (column) (μm)	390	390	390	390	390	390	390	390	390
Area %	90%	81%	70%	61%	47%	35%	26%	16%	10%

Example	26	27	28	29	30	31
Mask Width (mm)	0.4	0.3	0.22	0.22	0.22	0.22
Mask Gap (row) (μm)	60	60	60	200	500	800
Mask Gap (column) (μm)	250	250	250	250	250	250
Protrusion Width (μm)	260	160	80	80	80	80
Gap Width (row) (μm)	200	200	200	340	640	940
Minimum distance (column) (μm)	390	390	390	390	390	390
Area %	57%	44%	29%	19%	11%	8%

[0231] In FIGS. **22-24**, circle-shaped points (e.g., points **2211**, **2313**, **2315**, **2321**, **2413**, **2415**, **2417**, and **2421**) correspond to foldable substrates with protrusions arranged in a row extending for substantially the corresponding dimension of the foldable substrate (corresponding to the foldable substrate shown in FIG. **4**) referred to as "blocks" herein. In FIGS. **22-24**, the square-shaped points (e.g., points **2213**, **2317**, **2323**, **2419**, and **2423**) correspond to foldable substrates with protrusions arranged in a two-dimensional array with adjacent columns offset from one another (corresponding to the foldable substrate in FIG. **5**) referred to as "kerfs" herein. In FIGS. **23-24**, triangle shapes (e.g., points **2305** and **2405**) correspond to reference substrates. For

[0232] FIG. **22** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis **2203** (i.e., y-axis) as a function of an area ratio in percent (%) on the horizontal axis **2201** (i.e., x-axis). In FIG. **22**, dashed line **2209***a* corresponds to the impact resistance (2.8 kgf) of a reference substrate with a monolithic thickness of 100 μm, and line **2209***b* corresponds to the impact resistance (4.0 kgf) of a reference substrate having a monolithic thickness of 120 μm. As shown in FIG. **22**, all of the points **2205** shown for the example foldable substrates, including foldable substrates having the block design of protrusions (point **2211**) and the kerf design of protrusions (point **2213**), roughly follow the multi-segmented trendline **2207***a*-**2207***c*. The first segment of the trendline **2207***a* (for an area ratio less than about 55%) has a lower slope than the other segments of the multi-segmented trendline **2207***a*-**2207***c*. The middle segment **2207***b* extends between area ratios of about 55% to about 85% and has a steeper slope than the first segment **2207***a*. Based on the presentation of data in FIG. **22**, it would appear that protrusions associated with an area ratio from greater than 55% to about 85% has improved impact resistance per increase in area ratio. However, the second segment of the trendline **2207***b* appears to intersect line **2209***a* at an area ratio of about 70%, but the weighted average thickness for an area ratio of 70% is 106 μm, which is greater than the 100 μm thickness of the reference sample corresponding to line **2209***a*. Consequently, it would appear that foldable substrates with the plurality of protrusions do not provide benefits relative to a reference substrate with the same weighted average thickness (since a larger weighted average thickness of 106 μm has the same impact resistance of a 100 μm reference sample) in the region suggested by the multi-segmented trendline **2207***a*-**2207***c*. Based on these results, it is unlikely that a person having ordinary skill in the art would further investigate the designs using a plurality of protrusions in accordance with the present disclosure. However, as discussed in the following paragraphs with reference to FIGS. **23-24**, the inventors of the present disclosure have unexpectedly discovered improved impact resistance relative to comparative reference substrates.

[0233] FIG. **23** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis **2303** (i.e., y-axis) as a function of monolithic thickness (μm) of the reference samples on the horizontal axis **2301** (i.e., x-axis). For points **2313**, **2315**, **2317**, **2321**, and **2323** (e.g., clusters **2309** and **2311**), the position along the horizontal axis **2301** (i.e., x-axis) for the sample was determined based on a reference sample (or the calibration curve) with the same minimum parallel plate distance as the sample. As shown in FIG. **23**, calibration curve **2307** shows the trend of points **2305** corresponding to reference substrates with monolithic thicknesses from 40 μm to 140 μm. Cluster **2311** of points **2321** and **2323** correspond to area ratios greater than 80%, and cluster **2311** is below the calibration curve, indicating that there is no improvement in impact resistance relative to corresponding monolithic substrates. However, cluster **2309** of points **2313**, **2315**, and **2317** for area ratios from 10% to 70% (e.g., from 20% to 60%, or from 25% to 50%) are above the calibration curve **2307**. Being above the calibration curve corresponds to an improvement in impact resistance beyond what would be expected (or obtained) for a monolithic substrate having a minimum parallel plate distance equal to that of the foldable substrate. Especially in view of the trend observed in FIG. **22**, the improved impact resistance for cluster **2309** (being above calibration curve **2307**) is an unexpected benefit from providing the foldable substrate with the plurality of protrusions.

[0234] FIG. **24** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis **2403** (i.e., y-axis) as a function of parallel plate distance in millimeters (mm) on the horizontal axis **2401** (i.e., x-axis). As shown in FIG. **24**, calibration curve **2407** shows the trend of points **2405** corresponding to reference substrates with monolithic thicknesses having minimum parallel plate distances from about 4 mm to about 19 mm. Cluster **2411** of points **2421** and **2423** correspond to area ratios greater than 80%, and cluster **2411** is at or below the calibration curve, indicating that there is no improvement in impact resistance relative to monolithic substrates with a minimum parallel plate distance equal to that of the foldable substrate. However, cluster **2409** of points **2413**, **2415**, and **2417** for area ratios from 10% to 70% (e.g., from 20% to 60%, or from 25% to 50%) are above the calibration curve **2407**. Being above the calibration curve corresponds to an improvement in impact resistance beyond what would be expected (or obtained) for a monolithic substrate with a minimum parallel plate distance equal to that of the foldable substrate. Especially in view of the trend observed in FIG. **22**, the improved impact resistance for cluster **2409** (being above calibration curve **2407**) is an unexpected benefit from providing the foldable substrate with the plurality of protrusions.

[0235] FIG. **25** presents impact resistance as measured by the Quasi-Static Puncture Test in kilograms force (kgf) on the vertical axis **2503** (i.e., y-axis) as a function of area ratio in percent (%) on the horizontal axis **2501** (i.e., x-axis). Additional foldable substrates were fabricated for FIG. **25** (beyond those shown in FIGS. **23-24**) to further investigate the behavior of the block design and the kerf design within the range of unexpected benefits found from FIGS. **23-24** and to evaluate the effect of the central thickness of the impact resistance in these designs. Points **2505** correspond to foldable substrates with a central thickness of 80 μm (with the protrusions extending for 70 μm) while points **2511** correspond to foldable substrates with a central thickness of 120 μm (with the protrusions extending for 30 μm). Curve **2507** shows the trend of points **2505**, and curve **2513** shows the trend of points **2511**. As shown in FIG. **25**, points **2505** and curve **2507** show that the impact resistance increases with increasing area ratio (e.g., monotonically. However, the trend for increasing areas ratio (of area ratio less than 50%, 40%, and/or 30%) of points **2511** and curve **2513** (central thickness of 120 μm rather than 80 μm) appears to to be relatively flat or even downwardly inclined for relatively low area ratio. This suggests that larger central thickness (e.g., as a percentage of the substrate thickness) may further have unexpected benefits for low area ratio (e.g., from about 10% to about 50%, from 10% to 40%, from 10% to 30%, or from 10% to 20%).

[0236] The above observations can be combined to provide foldable substrate and/or foldable apparatus comprising foldable substrates, foldable substrates, and methods of making foldable apparatus and foldable substrates comprising foldable substrates that comprise a first portion, a second portion, and a central portion positioned therebetween. The foldable substrate can comprise glass-based and/or ceramic-based portions, which can provide good dimensional stability, reduced incidence of mechanical instabilities, good impact resistance, and/or good puncture resistance. The portions can comprise one or more compressive stress regions, which can further provide increased impact resistance and/or increased puncture resistance. By providing a foldable substrate comprising a glass-based and/or ceramic-based substrate, the foldable substrate can also provide increased impact resistance and/or puncture resistance while simultaneously facilitating good folding performance. In aspects, the substrate thickness can be sufficiently large (e.g., from about 50 micrometers (microns or μm) to about 2 millimeters) to further enhance impact resistance and puncture resistance. Providing foldable substrates comprising a central portion comprising a central thickness that is less than a substrate thickness (e.g., first thickness of the first portion and/or second thickness of the second portion) (e.g., by about 10 μm or more) can enable a small parallel plate distance (e.g., about 10 millimeters (mm) or less, about 5 mm or less, or about 3 mm or less) based on the reduced thickness in the central portion, which can enable the foldability and/or rollability of the foldable substrate and/or foldable apparatus.

[0237] In aspects, the foldable apparatus and/or foldable substrates can comprise a recess, for example, a first central surface area recessed from a first major surface by a first distance. Providing a recess can form a central thickness that is less than a substrate thickness, which can facilitate folding of the foldable substrate and/or foldable apparatus. Further, providing the recess (e.g., with the plurality of protrusions) on only one side of the foldable substrate can provide a uniform opposite surface that can present a smooth, consistent surface for a user to interact with.

[0238] The inventors of the present application have unexpectedly determined that providing a plurality of protrusions can improve impact resistance (e.g., as measured in the Quasi-Static Puncture Test) while allowing the foldable substrate and/or foldable substrate to still attain low parallel plate distances. Specifically, as discussed below with reference to FIG. **24**, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness with the same parallel plate distance (e.g., minimum parallel plate distance) (where the parallel plate distance and impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance without negatively impacting foldability (e.g., parallel plate distance). Also, area ratios have unexpectedly been identified where the impact resistance (e.g., as measured in the Quasi-Static Puncture Test) is greater than a reference sample having a monolithic thickness equal to a weighted average thickness (defined below) (where the impact resistance of the reference sample is either directly measured experimentally or based on a calibration curve from a plurality of reference substrates), which demonstrates that the plurality of protrusion can increase impact resistance beyond what would be achieved for a substrate with the same weighted average thickness. Being above the calibration curve corresponds to an improvement in impact resistance beyond what would be expected (or obtained) for a monolithic substrate with a minimum parallel plate distance equal to that of the foldable substrate. For example, providing an area ratio from 0.10 to 0.70 (e.g., from 0.20 to 0.60, or from 0.25 to 0.50) can unexpectedly provide improved impact resistance (e.g., as measured in the Quasi-Static Puncture Test), for example, relative to a reference substrate with the same parallel plate distance or with the same weighted average thickness. Also, providing a plurality of protrusions arranged such that there is not a protrusion of the plurality of protrusions impinged by the midline (e.g., fold plane **109**) can decrease a bend-induced stress on the foldable substrate.

[0239] Providing rounded corners for the cross-sectional shape of a protrusion of the plurality of protrusions can decrease stress concentrations at the corners of the protrusions, which can decrease a maximum bending stress associated with folding to a predetermined parallel plate distance and/or increase a reliability of folding the foldable substrate and/or foldable apparatus. Also, providing a plurality of protrusions (e.g., comprising substantially the substrate thickness) can increase a puncture resistance of the central region (e.g., due to the increased thickness of the plurality of protrusions relative to the first central surface area) while the central region (excluding the plurality of protrusions) can still facilitate folding of the foldable apparatus and/or foldable substrate. In further aspects, providing a plurality of substantially constant local thicknesses (e.g., substantially equal to the central thickness) between corresponding adjacent pairs of protrusions of the plurality of protrusions can simplify manufacturing, for example, enabling the local thickness between an adjacent pair of protrusions to be formed in a single etching step (e.g., with the portions corresponding to the adjacent pair of protrusions being masked).

[0240] Directional terms as used herein—for example, up, down, right, left, front, back, top, bottom—are made only with reference to the figures as drawn and are not intended to imply absolute orientation.

[0241] It will be appreciated that the various disclosed aspects may involve features, elements, or steps that are described in connection with that aspect. It will also be appreciated that a feature, element, or step, although described in relation to one aspect, may be interchanged or combined with alternate aspects in various non-illustrated combinations or permutations.

[0242] It is also to be understood that, as used herein the terms "the," "a," or "an," mean "at least one," and should not be limited to "only one" unless explicitly indicated to the contrary. For example, reference to "a component" comprises aspects having two or more such components unless the context clearly indicates otherwise. Likewise, a "plurality" is intended to denote "more than one."

[0243] As used herein, the term "about" means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. Ranges can be expressed herein as from "about" one particular value, and/or to "about" another particular value. When such a range is expressed, aspects include from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another aspect. Whether or not a numerical value or endpoint of a range in the specification recites "about," the numerical value or endpoint of a range is intended to include two aspects: one modified by "about," and one not modified by "about." It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint and independently of the other endpoint.

[0244] The terms "substantial," "substantially," and variations thereof as used herein are intended to note that a described feature is equal or approximately equal to a value or description. For example, a "substantially planar" surface is intended to denote a surface that is planar or approximately planar. Moreover, as defined above, "substantially similar" is intended to denote that two values are equal or approximately equal. In aspects, "substantially similar" may denote values within about 10% of each other, for example, within about 5% of each other, or within about 2% of each other.

[0245] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not actually recite an order to be followed by its steps or it is not otherwise specifically stated in the claims or descriptions that the steps are to be limited to a specific order, it is in no way intended that any particular order be inferred.

[0246] While various features, elements, or steps of particular aspects may be disclosed using the transitional phrase "comprising," it is to be understood that alternative aspects, including those that may be described using the transitional phrases "consisting of" or "consisting essentially of," are implied. Thus, for example, implied alternative aspects to an apparatus that comprises A+B+C include aspects where an apparatus consists of A+B+C and aspects where an apparatus consists essentially of A+B+C. As used herein, the terms "comprising" and "including", and variations thereof shall be construed as synonymous and open-ended unless otherwise indicated.

[0247] The above aspects, and the features of those aspects, are exemplary and can be provided alone or in any combination with any one or more features of other aspects provided herein without departing from the scope of the disclosure.

[0248] It will be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure cover the modifications and variations of the aspects herein provided they come within the scope of the appended claims and their equivalents.

What is claimed:

1. A foldable substrate comprising:

a substrate thickness defined between a first major surface and a second major surface opposite the first major surface in a thickness direction;

a first portion comprising the substrate thickness;

a second portion comprising the substrate thickness;

a central portion positioned between the first portion and the second portion, the central portion comprising a first central surface area and a second central surface area opposite the first central surface area, a central thickness defined between the first central surface area and the second central surface area in the thickness direction the central thickness is less than the substrate thickness; and

a plurality of protrusions extending from the first central surface area by at least 5 micrometers, each protrusion comprising an upper surface within 5 micrometers in the thickness direction from a point corresponding to a maximum height of the corresponding protrusion from the first central surface area;

a total protrusion area is a sum of an area of the upper surface of each protrusion of the plurality of protrusions, a total central area is an area of the central portion in a plane perpendicular to the thickness direction and impinging the first central surface area,

wherein the foldable substrate comprises a glass-based material or a ceramic-based material, and an area ratio of the total protrusion area to the total central area is from 0.10 to 0.70.

2. The foldable substrate of claim **1**, wherein the area ratio of the total protrusion area to the total central area is from 0.20 to 0.60.

3. The foldable substrate of claim **1**, wherein the foldable substrate achieves at least one of:

a minimum parallel plate distance in a Parallel Plate Test from 1 millimeter to 6 millimeters; or

a parallel plate distance in a Parallel Plate Test of 5 millimeters or less.

4. The foldable substrate of claim **1**, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test, a reference substrate comprises a monolithic thickness and achieves a reference minimum parallel plate distance in the Parallel Plate Test substantially equal to the minimum parallel plate distance of the foldable substrate, and a puncture resistance of the foldable substrate measured in a Quasi-Static Puncture Test is greater than a reference puncture resistance of the reference substrate measured in the Quasi-Static Puncture Test.

5. The foldable substrate of claim **1**, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as $TWA=(1-AR)*TC+AR*TP$, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a reference puncture resistance of a reference substrate comprising a uniform thickness equal to the weighted average thickness and the same material as the foldable substrate.

6. The foldable substrate of claim **1**, wherein the first major surface extends along a first plane, a first distance is defined between the first plane and the first central surface area in the thickness direction, a protrusion height defined between the first central surface area and the upper surface of a protrusion of the plurality of protrusions in the thickness direction, and the first distance is greater than or equal to the protrusion height.

7. The foldable substrate of claim **1**, wherein a width of the upper surface of a protrusion of the plurality of protrusions in a direction between the first portion and the second portion is from 20 micrometers to 1 millimeter.

8. The foldable substrate of claim **1**, wherein the plurality of protrusions are aligned in a row extending in a first direction between the first portion and the second portion.

9. The foldable substrate of claim **8**, wherein the plurality of protrusions are arranged in a two-dimensional array including the row extending between the first portion and the second portion, at least three protrusions of the plurality of protrusions in a column of a plurality of columns extending perpendicular to the row, and the protrusions of the plurality of protrusions in a first column of the plurality of columns is offset from corresponding protrusions of a second column of the plurality of columns, where the first column is adjacent to the second column.

10. The foldable substrate of claim **9**, wherein a gap width between adjacent protrusions in the row in the first direction is from 150 micrometers to 1 millimeter.

11. The foldable substrate of claim **1**, wherein the second major surface is flush with the second central surface area.

12. The foldable substrate of claim **1**, further comprising:

a first compressive stress region extending to a first depth of compression from the first major surface in the first portion;

a second compressive stress region extending to a second depth of compression from the second major surface in the first portion;

a third compressive stress region extending to a third depth of compression from the first major surface in the second portion;

a fourth compressive stress region extending to a fourth depth of compression from the second major surface in the second portion;

a first central compressive stress region extending to a first central depth of compression from the first central surface area; and

a second central compressive stress region extending to a second central depth of compression from the second central surface area.

13. A consumer electronic product, comprising:

a housing comprising a front surface, a back surface, and a side surface;

electrical components at least partially within the housing, the electrical components comprising a controller, a memory, and a display, the display at or adjacent the front surface of the housing; and

a cover substrate disposed over the display,

wherein at least one of a portion of the housing or the cover substrate comprises the foldable substrate of claim **1**.

14. A method of making a foldable substrate comprising:

disposing a patterned mask on a central portion of an initial major surface of an initial substrate, the patterned mask comprising a plurality of separate sections; and

etching the initial major surface of the initial substrate to form a central portion of the foldable substrate with a plurality of protrusions extending from a first central surface area by at least 5 micrometers, and the plurality of protrusions corresponding to the plurality of separate sections of the patterned mask on central portion of the initial major surface,

wherein each protrusion of the plurality of protrusions comprising an upper surface within 5 micrometers in the thickness direction from a point corresponding to a maximum height of the corresponding protrusion from the first central surface area,

a total protrusion area is a sum of sum of an area of the upper surface of each protrusion of the plurality of protrusions, a total central area is an area of the central portion in the plane perpendicular to the thickness direction and impinging the first central surface area, the foldable substrate comprises a glass-based material or a ceramic-based material, and an area ratio of the total protrusion area to the total central area is from 0.10 to 0.70.

15. The method of claim **14**, wherein the disposing the patterned mask comprises ink-jet printing the patterned mask.

16. The method of claim **14**, wherein the plurality of sections are aligned in a row extending in a first direction, the plurality of sections are arranged in a two-dimensional array including the row, at least three sections of the plurality of sections are in a column of a plurality of columns extending perpendicular to the row, and sections of the plurality of sections in a first column of the plurality of columns is offset from corresponding section of a second column of the plurality of columns, where the first column is adjacent to the second column.

17. The method of claim **14**, wherein the foldable substrate comprises:

a substrate thickness defined between the first major surface and a second major surface opposite the first major surface in a thickness direction;

a first portion comprising the substrate thickness;

a second portion comprising the substrate thickness; and

a central portion positioned between the first portion and the second portion, the central portion comprising the first central surface area and a second central surface area opposite the first central surface area, a central thickness defined between the first central surface area and the second central surface area in the thickness direction the central thickness is less than the substrate thickness.

18. The method of claim **17**, wherein the foldable substrate achieves a minimum parallel plate distance in a Parallel Plate Test, a reference substrate comprises a monolithic thickness and achieves a reference minimum parallel plate distance in the Parallel Plate Test substantially equal to the minimum parallel plate distance of the foldable substrate, and a puncture resistance of the foldable substrate measured in a Quasi-Static Puncture Test is greater than a reference puncture resistance of the reference substrate measured in the Quasi-Static Puncture Test.

19. The method of claim **17**, wherein the foldable substrate exhibits a puncture resistance measured in a Quasi-Static Puncture Test, a weighted average thickness TWA of the central portion defined as $TWA=(1-AR)*TC+AR*TP$, wherein AR is the area ratio, TC is the central thickness, and TP is a combined protrusion thickness defined between the second central surface area of the central portion and the upper surface of a protrusion of the plurality of protrusions, and the puncture resistance is greater than a reference puncture resistance of a reference substrate comprising a uniform thickness equal to the weighted average thickness and the same material as the foldable substrate.

20. The method of claim **14**, further comprising chemically strengthening the foldable substrate by simultaneously exposing the first major surface, the first central surface area, and the plurality of protrusions to a molten salt solution,

wherein the chemically strengthening forms:

a first compressive stress region extending to a first depth of compression from the first major surface in the first portion;

a second compressive stress region extending to a second depth of compression from the first major surface in the second portion; and

a first central compressive stress region extending to a first central depth of compression from the first central surface area.

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