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(54) **METHODS TO FABRICATE 2D WEDGE AND LOCALIZED ENCAPSULATION FOR DIFFRACTIVE OPTICS**

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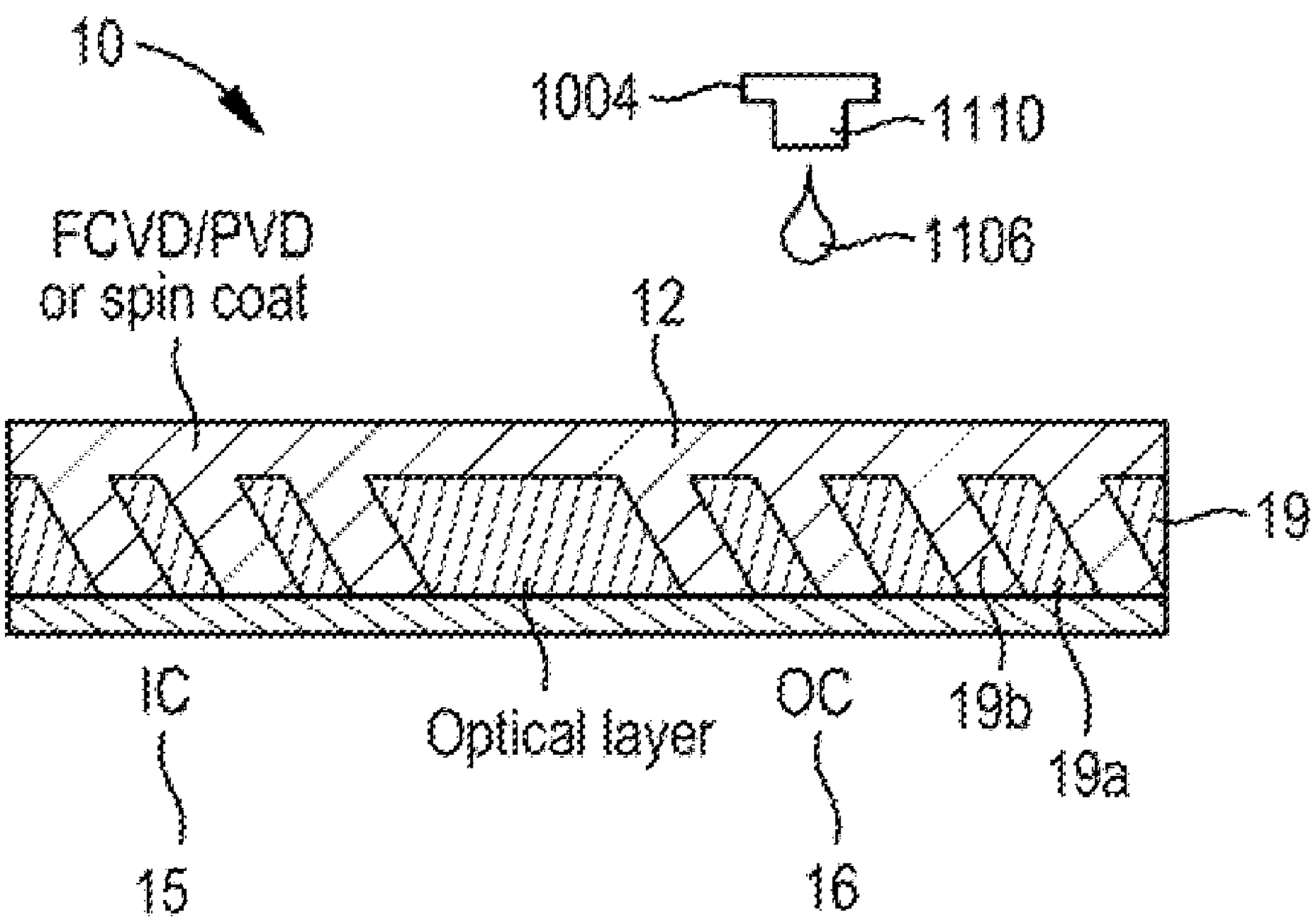
G02B 6/34 (2006.01)

(52) **U.S. Cl.**

CPC ***G03F 7/30*** (2013.01); ***G02B 6/34*** (2013.01)

(57) **ABSTRACT**

A method of forming a three dimensional feature inwardly of a surface of a material includes providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material having a reactant therein capable of reacting with, and thereby removing, portions of the material layer with which the droplets come into contact, providing a support configured support the material thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material, and positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the surface of the material in a desired area thereof, to remove at least a portion of the material in the desired area and thereby form a three dimensional recess inwardly of the surface of the material.



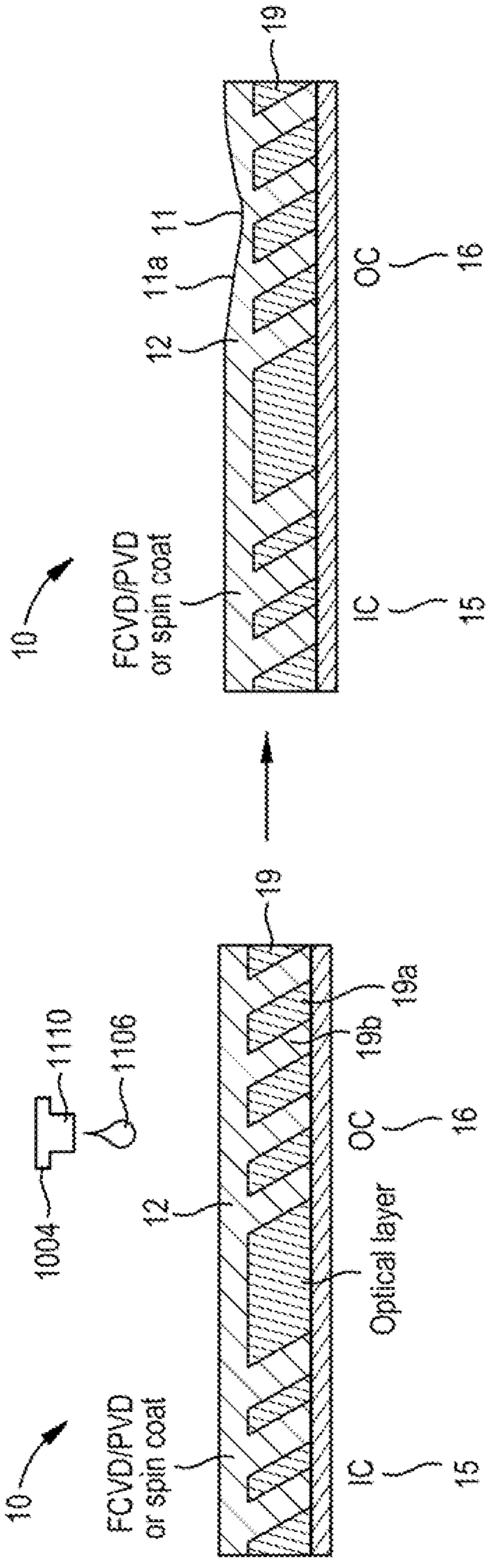

10
FCVD/PVD
or spin coat
IC
15
OC
16
19
11
11a
12
1004
1106
1110
19a
19b
Optical layer

FIG. 1A

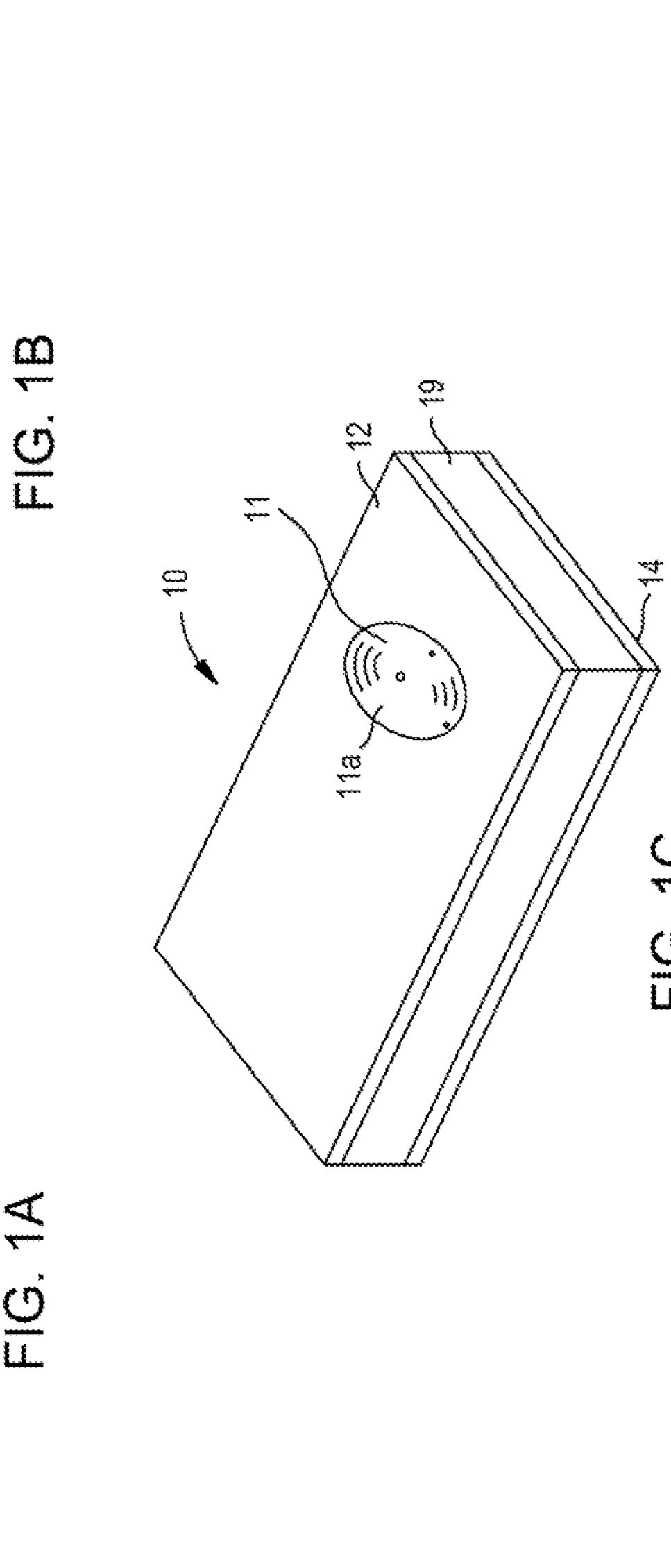

10
11
11a
12
14
19

FIG. 1C

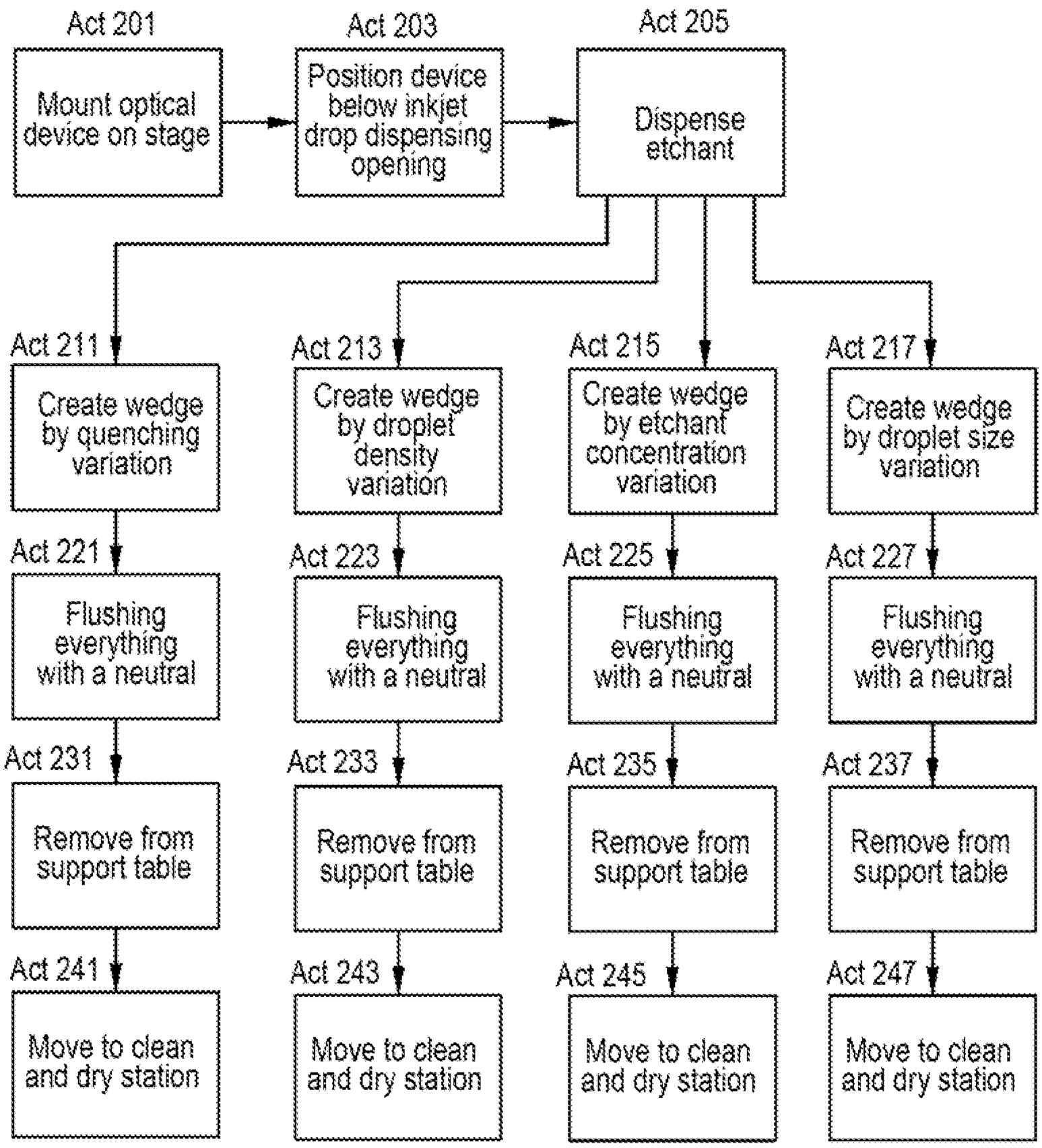

Act 201
Mount optical device on stage
Act 203
Position device below inkjet drop dispensing opening
Act 205
Dispense etchant
Act 211
Create wedge by quenching variation
Act 213
Create wedge by droplet density variation
Act 215
Create wedge by etchant concentration variation
Act 217
Create wedge by droplet size variation
Act 221
Flushing everything with a neutral
Act 223
Flushing everything with a neutral
Act 225
Flushing everything with a neutral
Act 227
Flushing everything with a neutral
Act 231
Remove from support table
Act 233
Remove from support table
Act 235
Remove from support table
Act 237
Remove from support table
Act 241
Move to clean and dry station
Act 243
Move to clean and dry station
Act 245
Move to clean and dry station
Act 247
Move to clean and dry station

FIG. 2

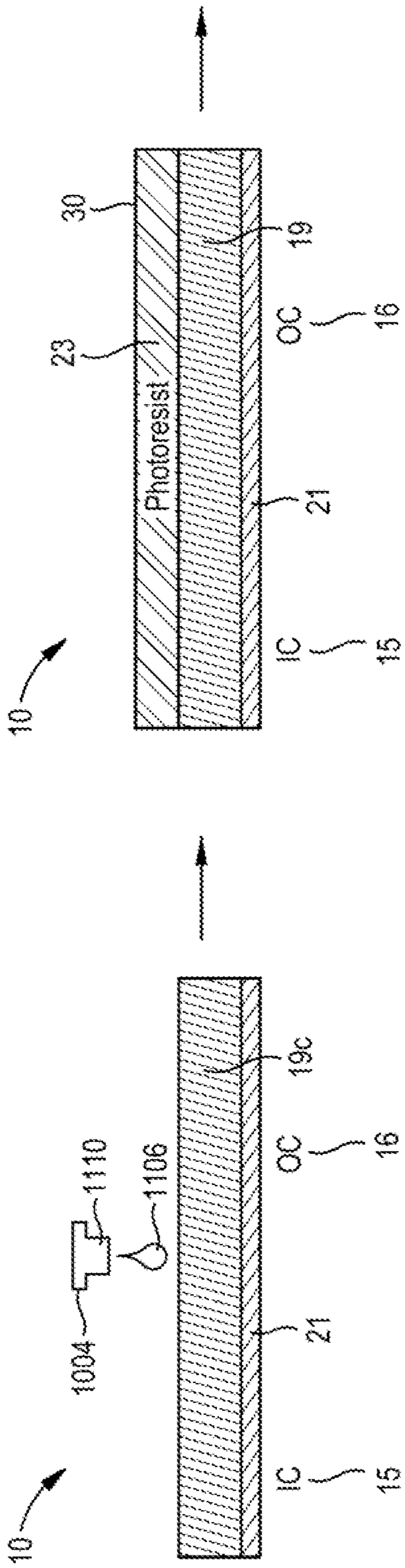


FIG. 3A

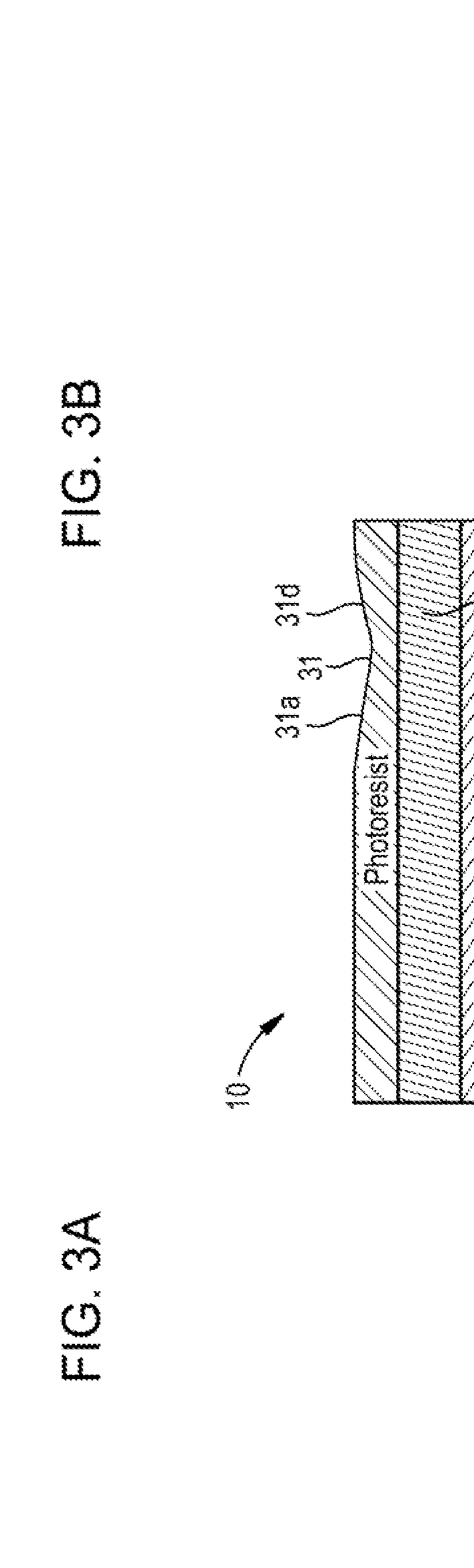


FIG. 3B

FIG. 3C

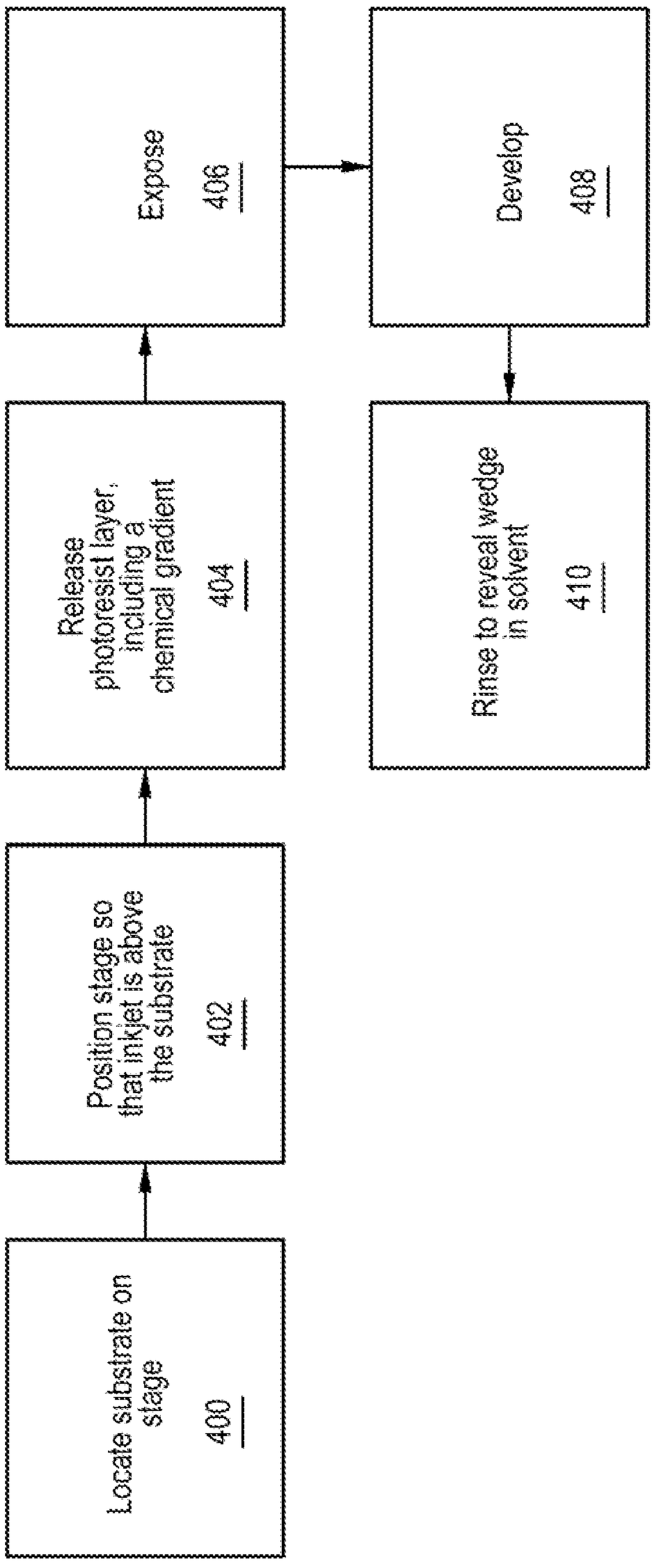

Locate substrate on stage
400
Position stage so that inkjet is above the substrate
402
Release photoresist layer, including a chemical gradient
404
Expose
406
Develop
408
Rinse to reveal wedge in solvent
410

FIG. 4

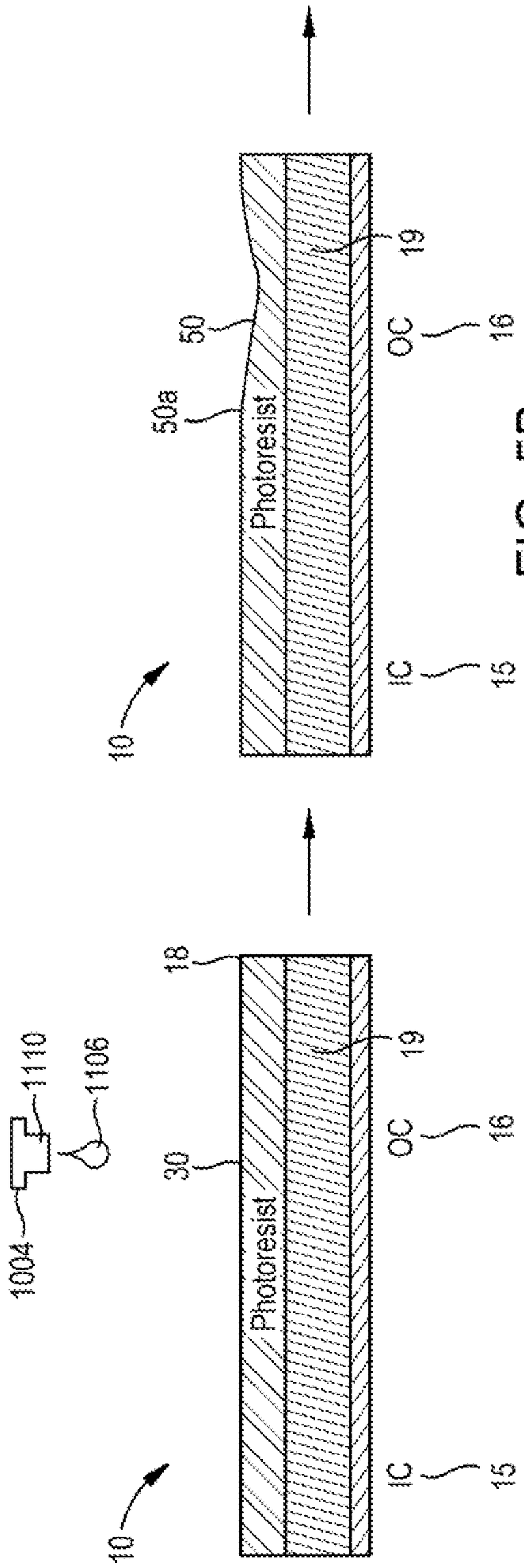


FIG. 5A

FIG. 5B

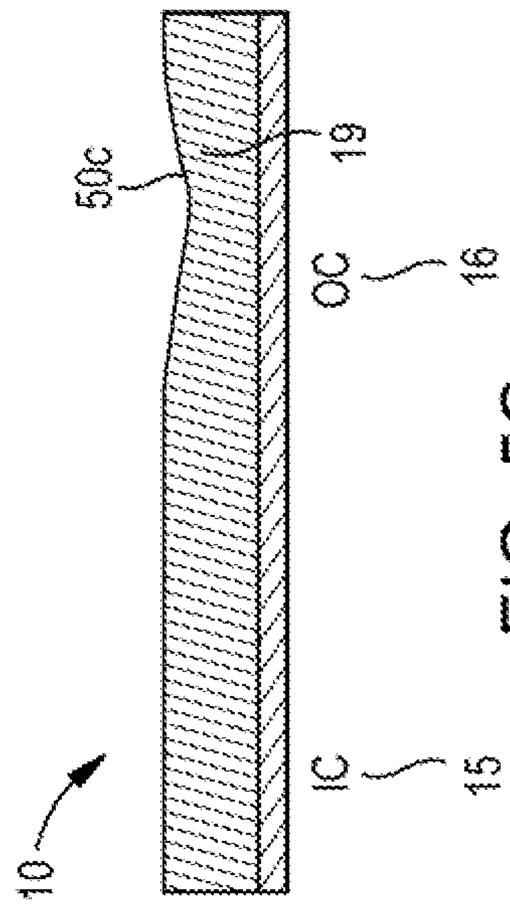


FIG. 5C

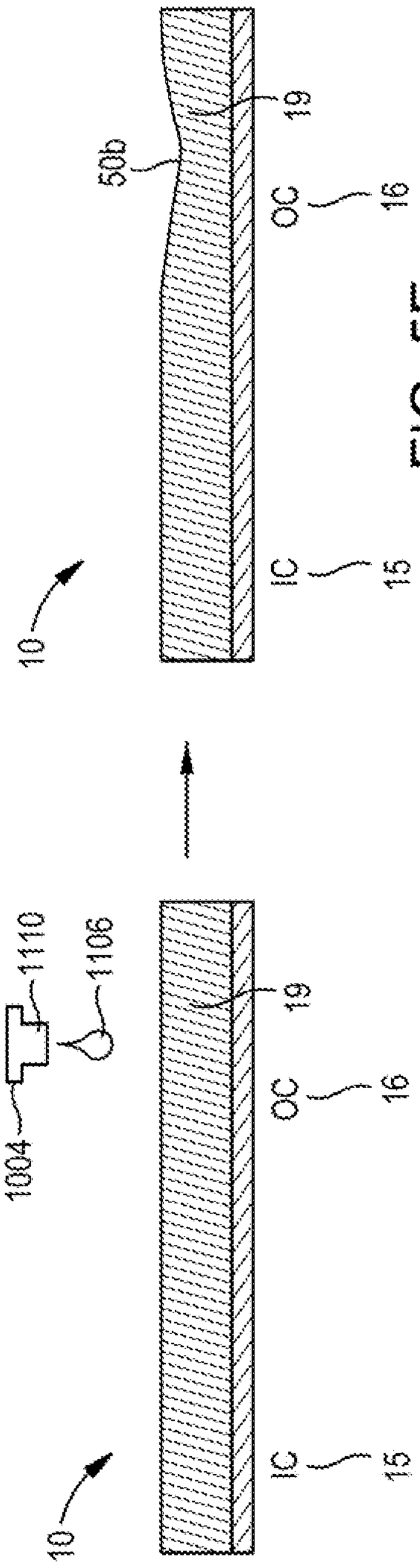


FIG. 5E

FIG. 5D

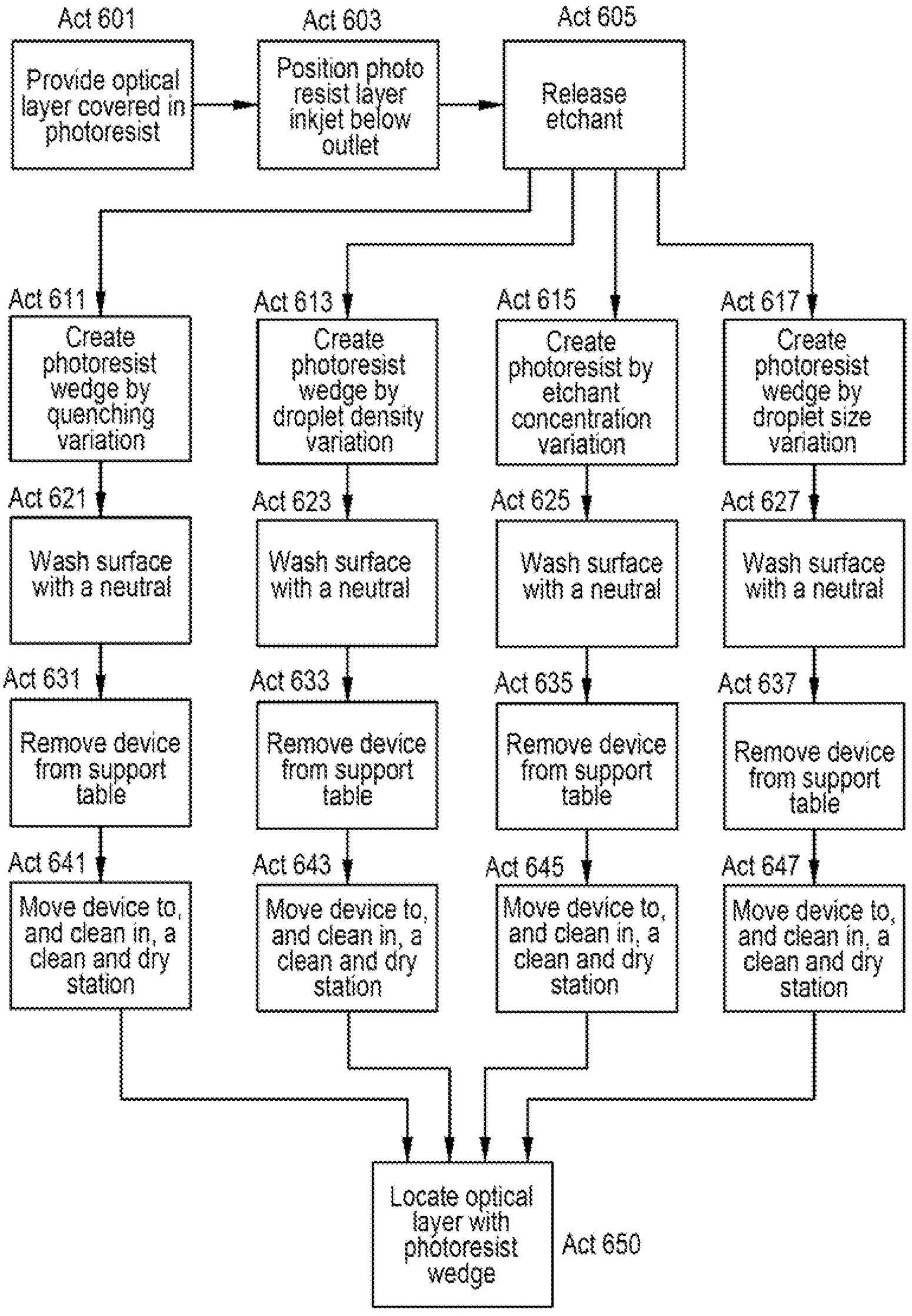

Act 601
Provide optical layer covered in photoresist
Act 603
Position photo resist layer inkjet below outlet
Act 605
Release etchant
Act 611
Create photoresist wedge by quenching variation
Act 613
Create photoresist wedge by droplet density variation
Act 615
Create photoresist by etchant concentration variation
Act 617
Create photoresist wedge by droplet size variation
Act 621
Wash surface with a neutral
Act 623
Wash surface with a neutral
Act 625
Wash surface with a neutral
Act 627
Wash surface with a neutral
Act 631
Remove device from support table
Act 633
Remove device from support table
Act 635
Remove device from support table
Act 637
Remove device from support table
Act 641
Move device to, and clean in, a clean and dry station
Act 643
Move device to, and clean in, a clean and dry station
Act 645
Move device to, and clean in, a clean and dry station
Act 647
Move device to, and clean in, a clean and dry station
Locate optical layer with photoresist wedge
Act 650

FIG. 6A

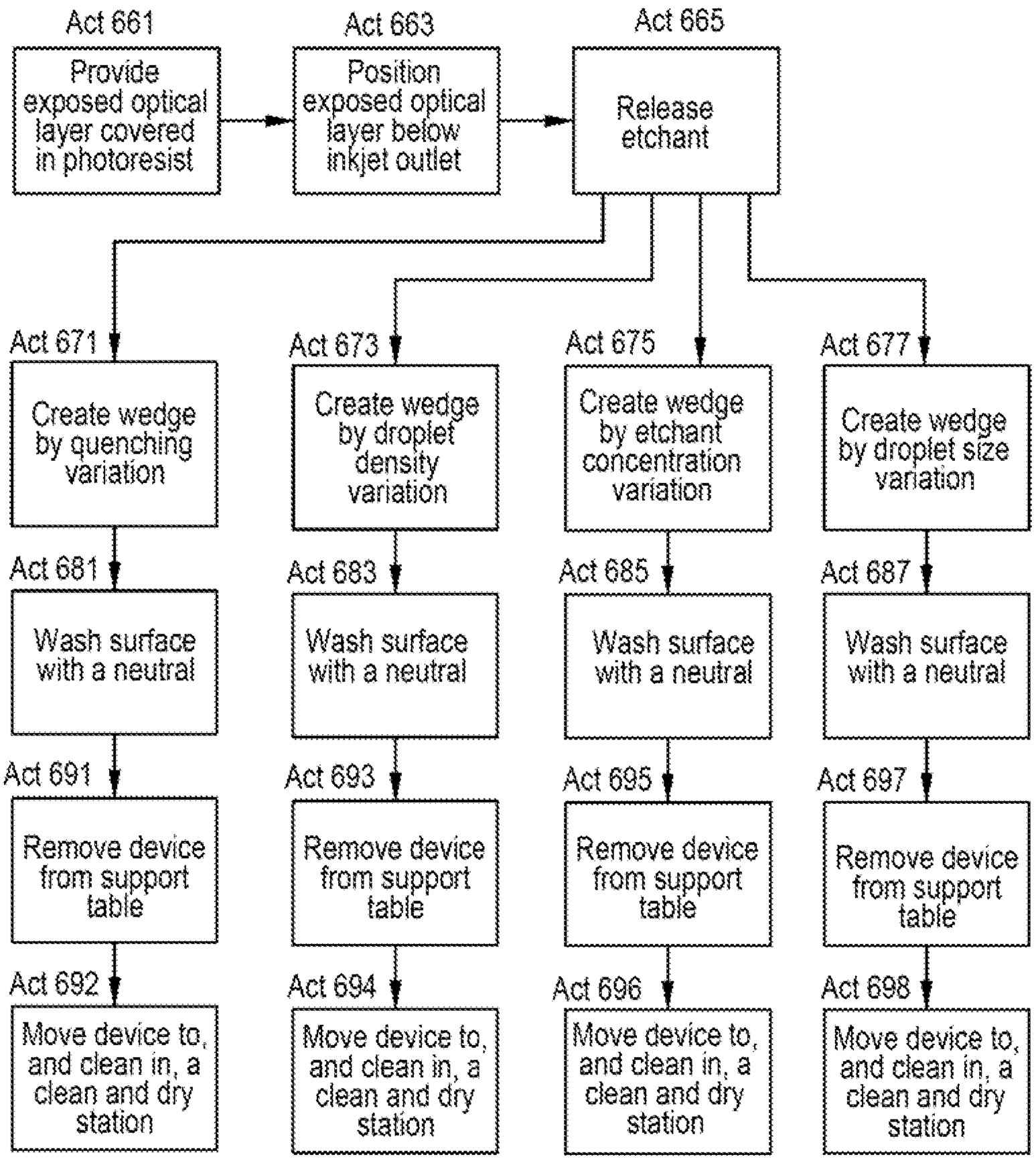

Act 661
Provide exposed optical layer covered in photoresist
Act 663
Position exposed optical layer below inkjet outlet
Act 665
Release etchant
Act 671
Create wedge by quenching variation
Act 673
Create wedge by droplet density variation
Act 675
Create wedge by etchant concentration variation
Act 677
Create wedge by droplet size variation
Act 681
Wash surface with a neutral
Act 683
Wash surface with a neutral
Act 685
Wash surface with a neutral
Act 687
Wash surface with a neutral
Act 691
Remove device from support table
Act 693
Remove device from support table
Act 695
Remove device from support table
Act 697
Remove device from support table
Act 692
Move device to, and clean in, a clean and dry station
Act 694
Move device to, and clean in, a clean and dry station
Act 696
Move device to, and clean in, a clean and dry station
Act 698
Move device to, and clean in, a clean and dry station

FIG. 6B

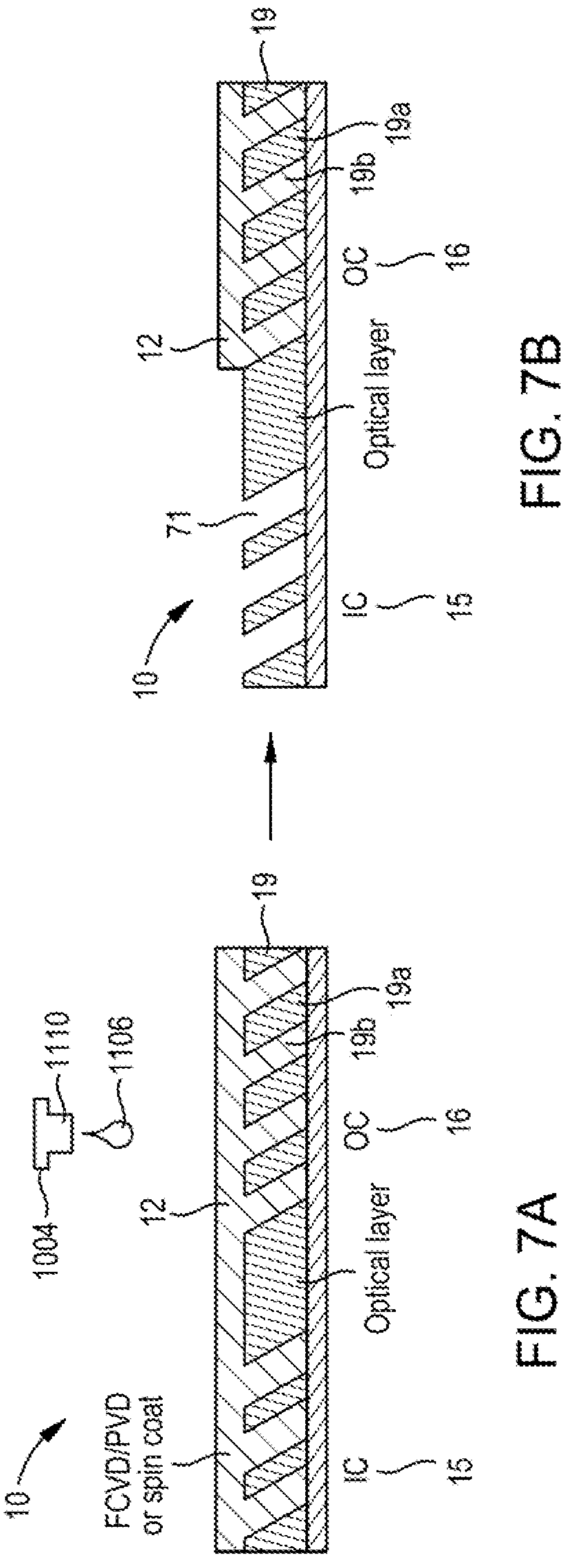

19
19a
19b
OC
16
12
Optical layer
71
IC
15
10
1004
1110
1106
FCVD/PVD
or spin coal

FIG. 7B

FIG. 7A

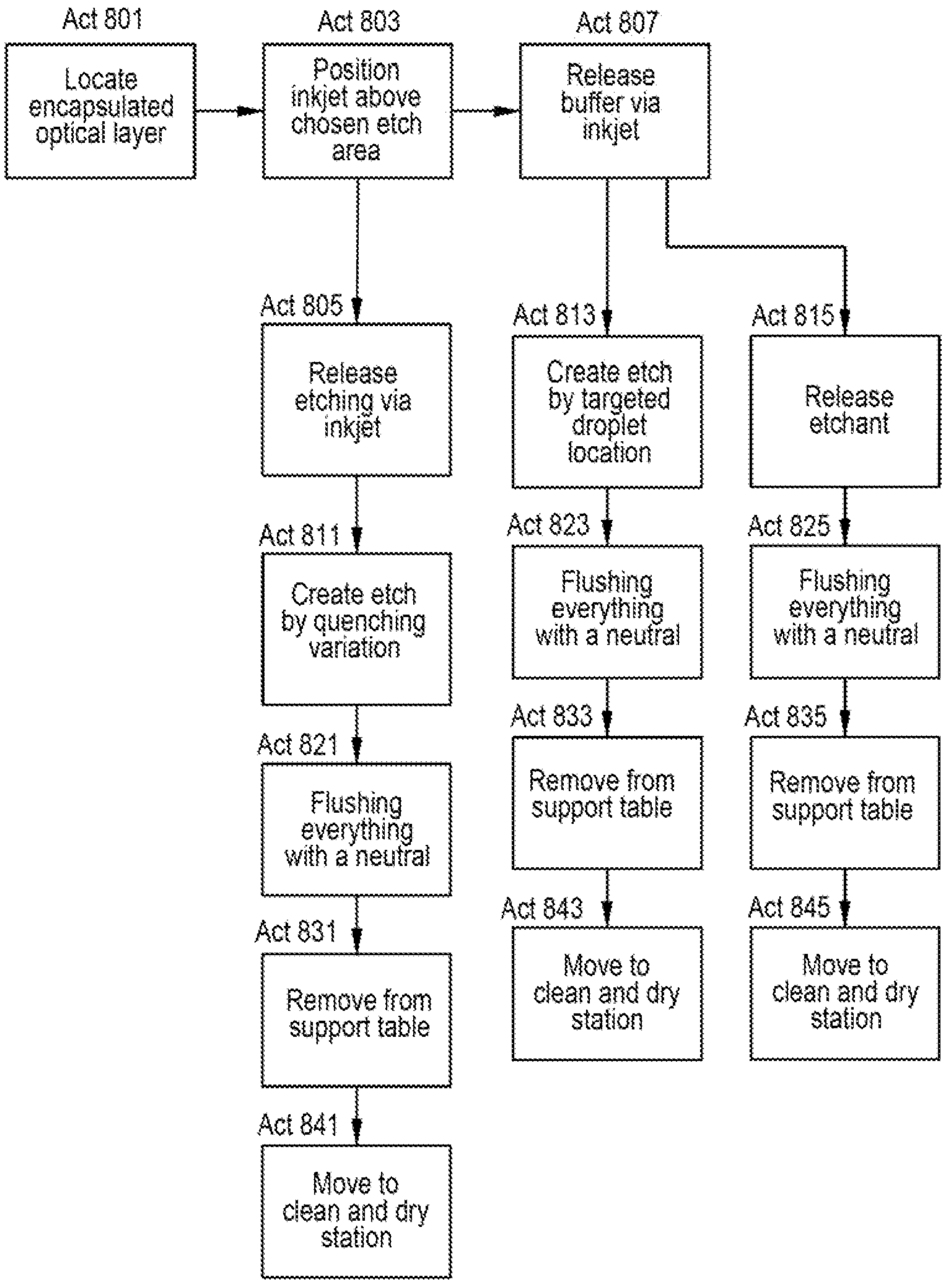

Act 801
Locate encapsulated optical layer
Act 803
Position inkjet above chosen etch area
Act 807
Release buffer via inkjet
Act 805
Release etching via inkjet
Act 811
Create etch by quenching variation
Act 821
Flushing everything with a neutral
Act 831
Remove from support table
Act 841
Move to clean and dry station
Act 813
Create etch by targeted droplet location
Act 823
Flushing everything with a neutral
Act 833
Remove from support table
Act 843
Move to clean and dry station
Act 815
Release etchant
Act 825
Flushing everything with a neutral
Act 835
Remove from support table
Act 845
Move to clean and dry station

FIG. 8

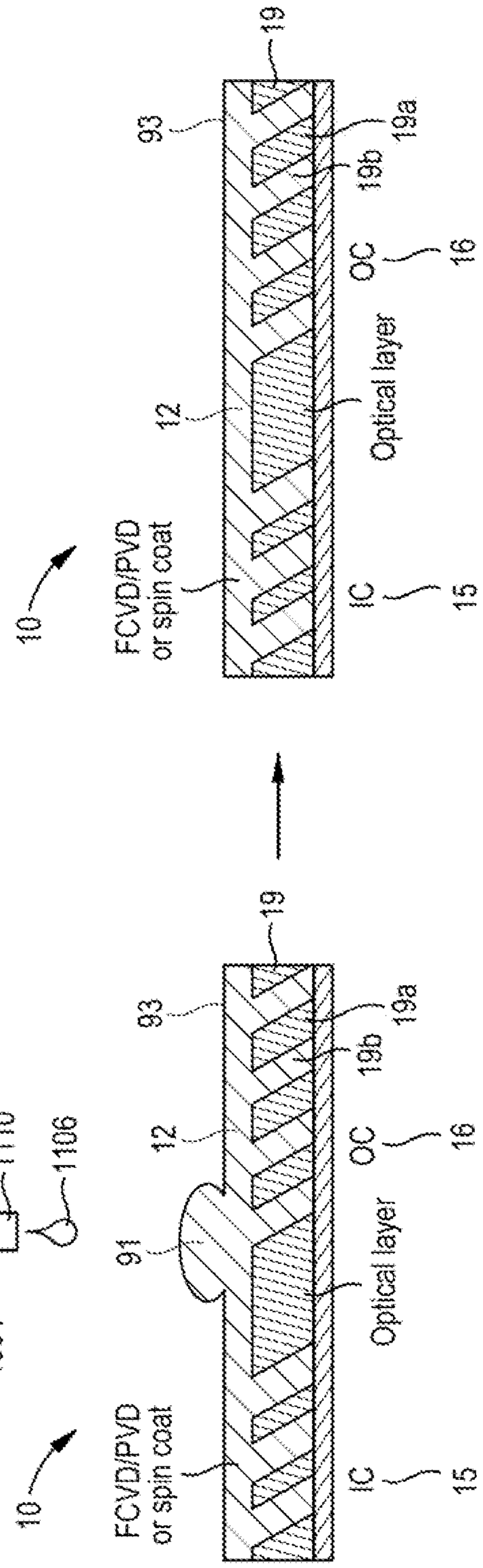

19
93
19a
19b
OC
16
12
Optical layer
10
FCVD/PVD
or spin coat
IC
15

FIG. 9B

19
93
19a
19b
1004
1110
1106
91
12
OC
16
Optical layer
10
FCVD/PVD
or spin coat
IC
15

FIG. 9A

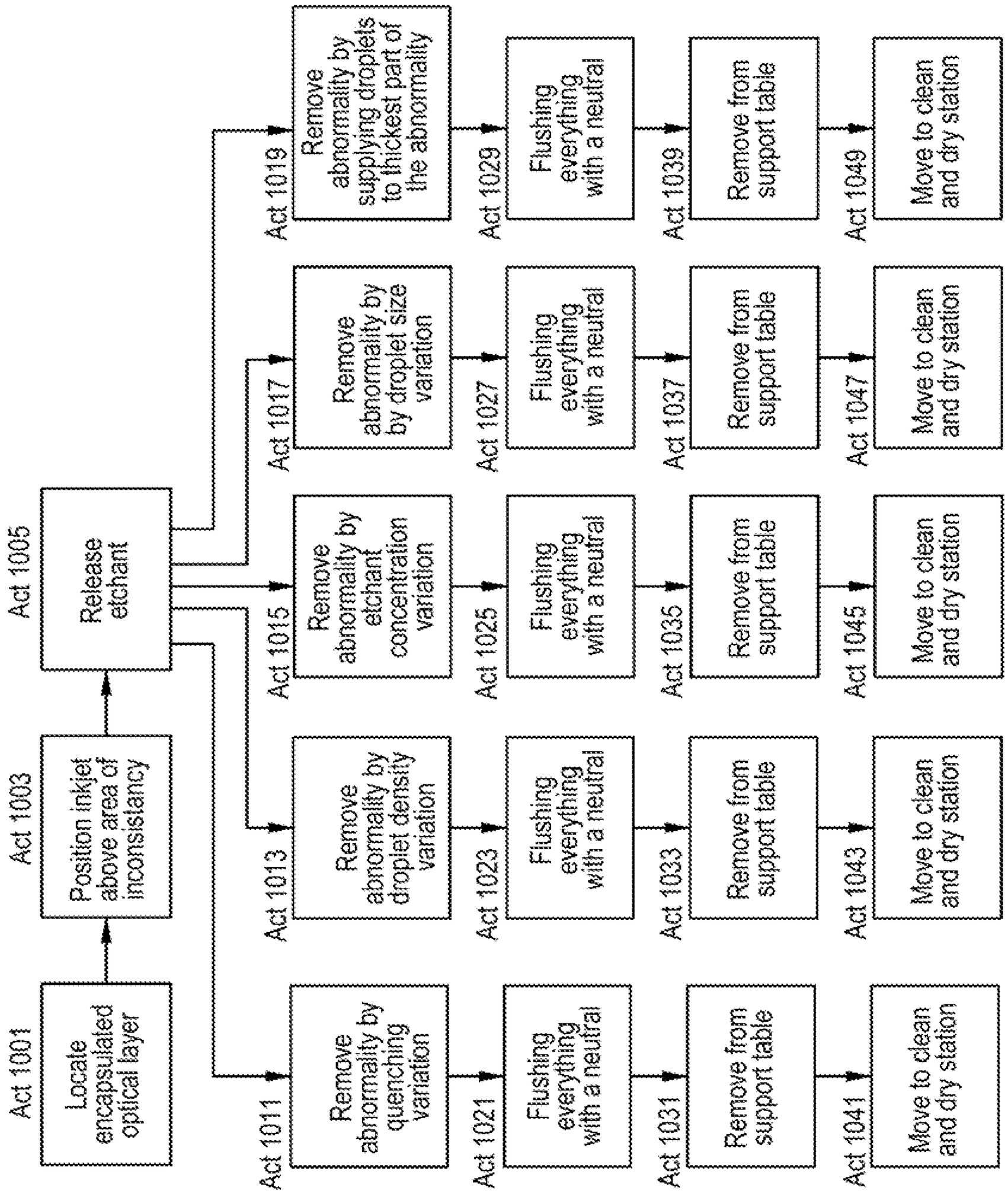

Act 1001
Locate encapsulated optical layer
Act 1003
Position inkjet above area of inconsistancy
Act 1005
Release etchant
Act 1011
Remove abnormality by quenching variation
Act 1013
Remove abnormality by droplet density variation
Act 1015
Remove abnormality by etchant concentration variation
Act 1017
Remove abnormality by by droplet size variation
Act 1019
Remove abnormality by supplying droplets to thickest part of the abnormality
Act 1021
Flushing everything with a neutral
Act 1023
Flushing everything with a neutral
Act 1025
Flushing everything with a neutral
Act 1027
Flushing everything with a neutral
Act 1029
Flushing everything with a neutral
Act 1031
Remove from support table
Act 1033
Remove from support table
Act 1035
Remove from support table
Act 1037
Remove from support table
Act 1039
Remove from support table
Act 1041
Move to clean and dry station
Act 1043
Move to clean and dry station
Act 1045
Move to clean and dry station
Act 1047
Move to clean and dry station
Act 1049
Move to clean and dry station

FIG. 10

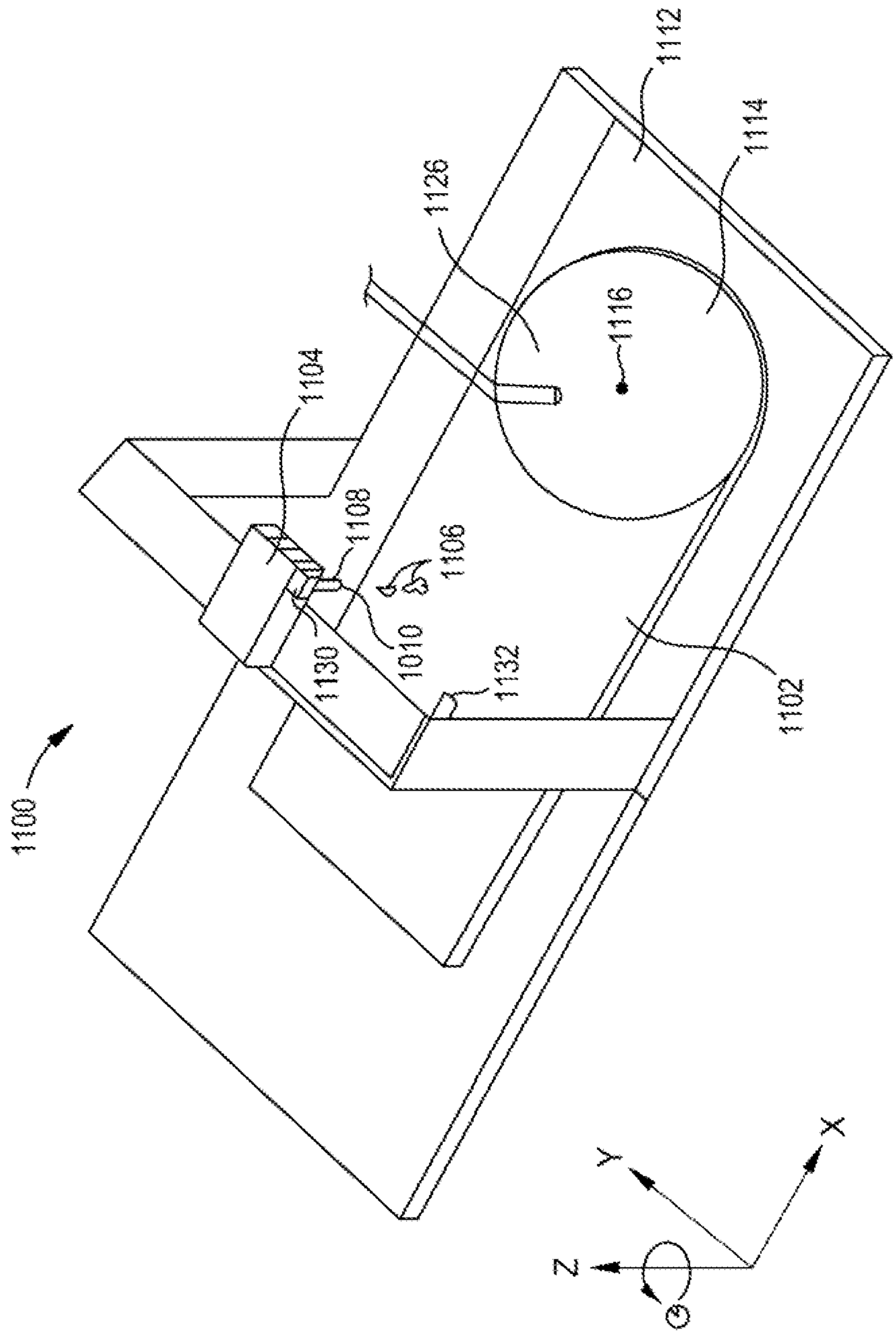

1100
1102
1104
1106
1108
1010
1112
1114
1116
1126
1130
1132
X
Y
Z
θ

FIG. 11

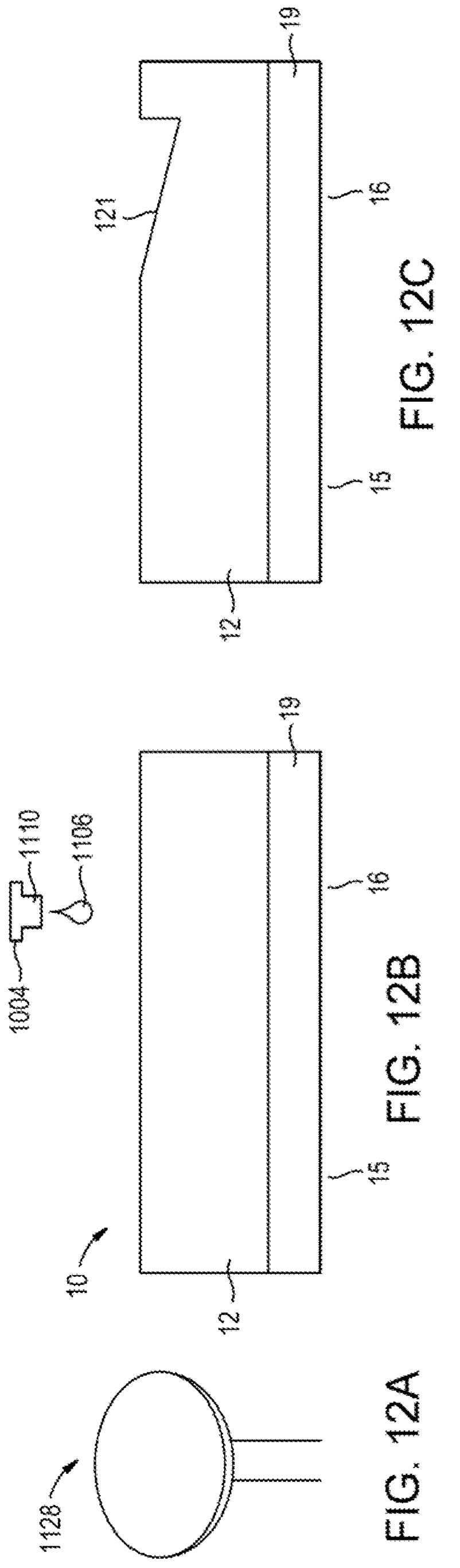


FIG. 12A

FIG. 12B

FIG. 12C

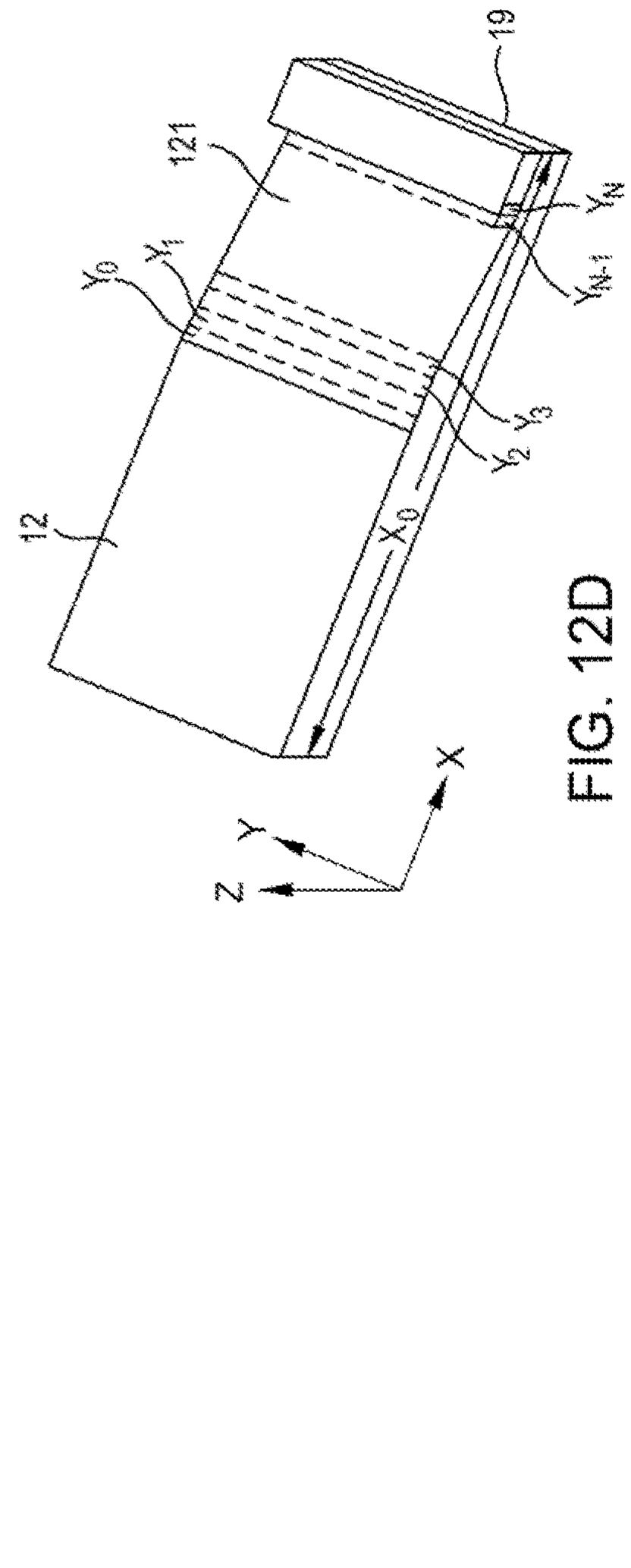


FIG. 12D

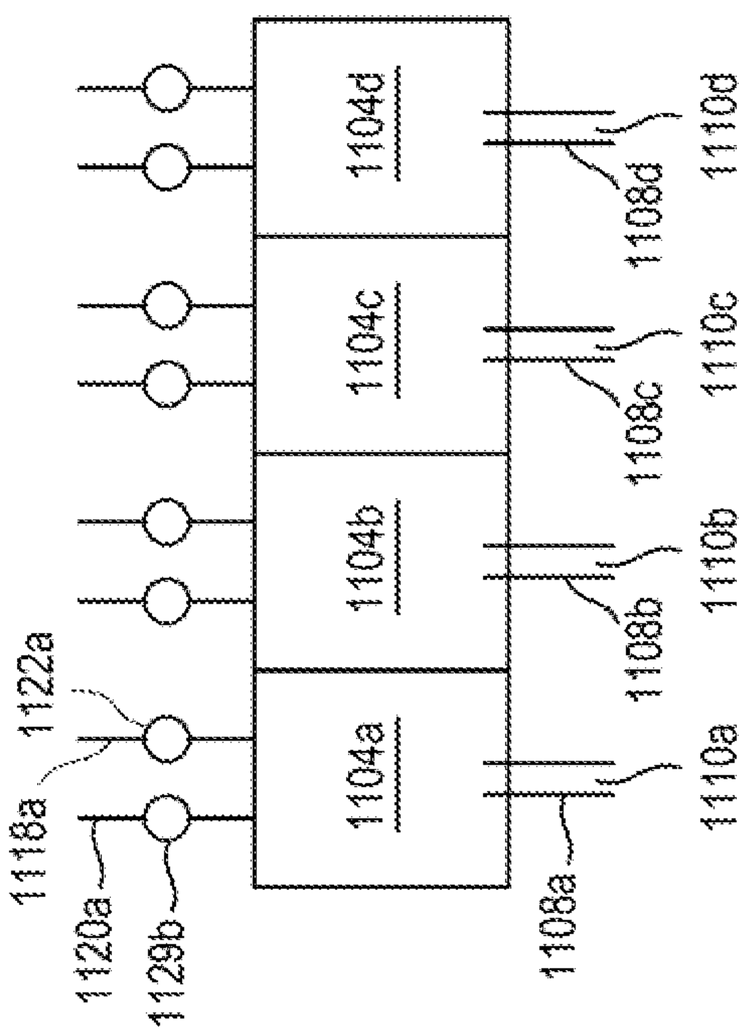

1118a
1122a
120a
29b
1104a
1104b
1104c
1104d
1108a
1108b
1108c
1108d
1110a
1110b
1110c
1110d

FIG. 13

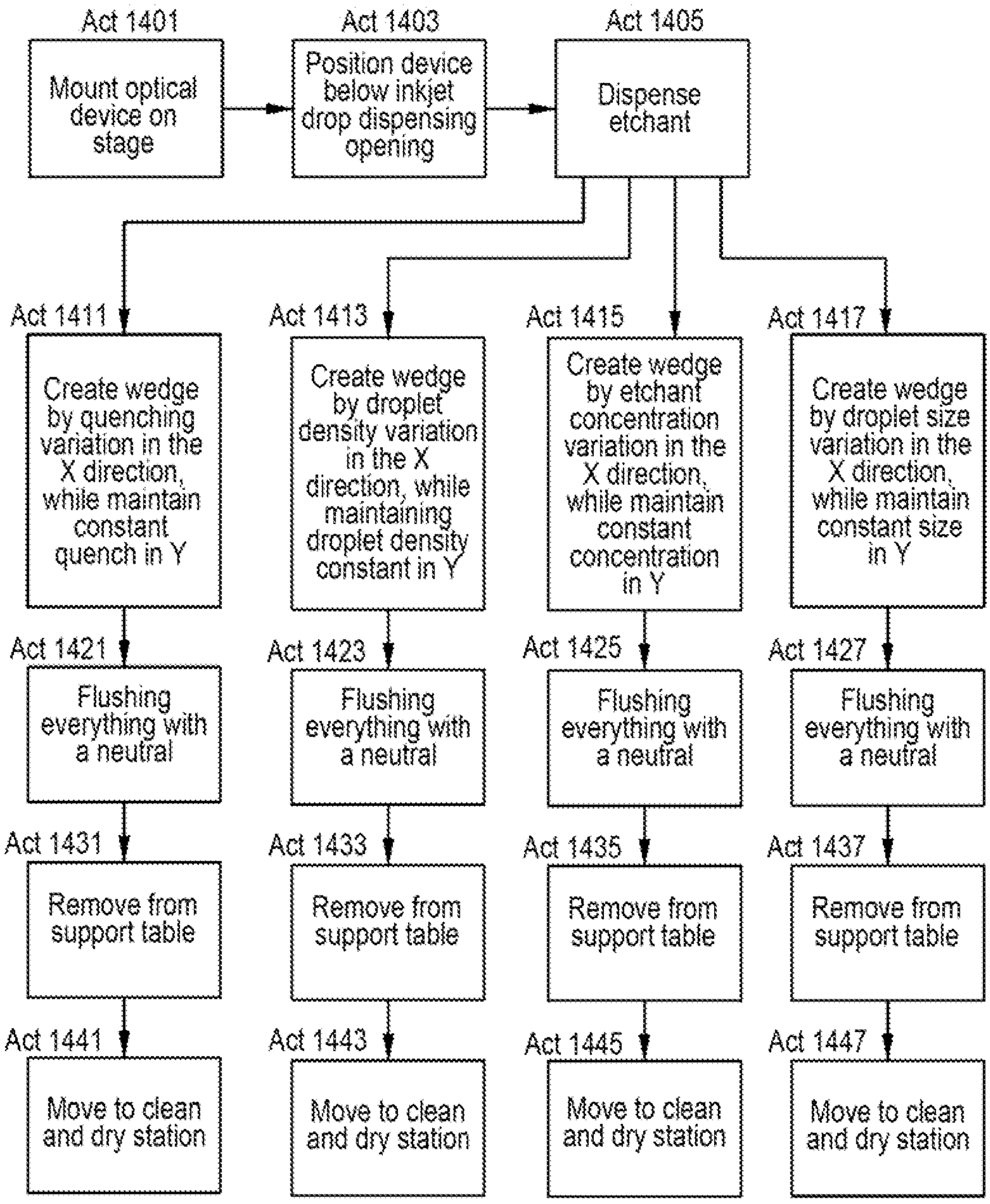

Act 1401
Mount optical device on stage
Act 1403
Position device below inkjet drop dispensing opening
Act 1405
Dispense etchant
Act 1411
Create wedge by quenching variation in the X direction, while maintain constant quench in Y
Act 1413
Create wedge by droplet density variation in the X direction, while maintaining droplet density constant in Y
Act 1415
Create wedge by etchant concentration variation in the X direction, while maintain constant concentration in Y
Act 1417
Create wedge by droplet size variation in the X direction, while maintain constant size in Y
Act 1421
Flushing everything with a neutral
Act 1423
Flushing everything with a neutral
Act 1425
Flushing everything with a neutral
Act 1427
Flushing everything with a neutral
Act 1431
Remove from support table
Act 1433
Remove from support table
Act 1435
Remove from support table
Act 1437
Remove from support table
Act 1441
Move to clean and dry station
Act 1443
Move to clean and dry station
Act 1445
Move to clean and dry station
Act 1447
Move to clean and dry station

FIG. 14

METHODS TO FABRICATE 2D WEDGE AND LOCALIZED ENCAPSULATION FOR DIFFRACTIVE OPTICS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 63/059,826, filed Jul. 31, 2020 and U.S. Provisional Patent Application No. 63/081,961, filed Sep. 23, 2020, both of which are incorporated herein by reference in its entirety.

BACKGROUND

Field

[0002] The present disclosure generally relates to selective wet etching of multi-dimensional features inwardly of a material surface, more particularly to dispensing individual droplets of a material removal chemistry to discrete portions of a material surface to form multi-dimensional recess features therein in controlled, discrete, regions thereof.

Description of the Related Art

[0003] Three dimensional features extending inwardly of a material layer surface are useful in a number of applications, for example for forming a 2D wedge in a surface of an optical device to create diffractive optics including for example waveguide combiners and flat optics, among other applications. In some case, these features are created in an optical device to allow incouplers, outcouplers, or both, to allow light to enter or leave an optical layer of the optical device. There is a need to more precisely locate these features, with a repeatable geometric profile, from device to device, using a wet removal chemistry, such as a wet etchant, without the need to process the substrate to form an etch mask thereon.

SUMMARY

[0004] In one aspect, a method of forming a three dimensional feature inwardly of a surface of a material includes providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material having a reactant therein capable of reacting with, and thereby removing, portions of the material layer with which the droplets come into contact, providing a support configured support the material thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material, and positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the surface of the material in a desired area thereof, to remove at least a portion of the material in the desired area and thereby form a three dimensional recess inwardly of the surface of the material.

[0005] In another aspect, a method of forming a patterned photoresist on a material layer includes providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material therefrom, providing a support configured support the material layer thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material, providing a first liquid, dispensable from the droplet dispenser in droplet form, comprising a photoresist polymer, providing a second liquid, comprising a sensitizer which, when intermixed with the polymer, changes a reactivity of the polymer to electromagnetic energy, and positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the first liquid to the entire surface of the material layer, and dispensing droplets of the second liquid only on a desired, discrete area of the material layer to intermingle the first liquid and the second liquid in the desired, discrete area of the material layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1**A is a sectional view of an optical device with an optical layer and encapsulation layer.

[0007] FIG. **1**B is a sectional view of an optical device with an optical layer and encapsulation layer with a 2D wedge formed therein.

[0008] FIG. **1**C is an isometric view of the optical device of FIG. **1**B having the optical layer and encapsulation layer with a 2D wedge formed therein.

[0009] FIG. **2** is a flowchart showing a method for manufacturing a 2D wedge on an optical device, for example the 2D wedge of FIGS. **1**B and **1**C.

[0010] FIG. **3**A is a sectional view of an optical device with an optical layer thereon.

[0011] FIG. **3**B is a sectional view of an optical device with an optical layer and a photoresist layer formed over the optical layer.

[0012] FIG. **3**C is a sectional view of an optical device with an optical layer and photoresist layer with a 2D feature formed therein.

[0013] FIG. **4** is a flowchart showing a method for manufacturing the photoresist layer with a 2D feature formed therein of FIG. **3**C.

[0014] FIG. **5**A is a sectional view of an optical device with an optical layer and photoresist layer thereover.

[0015] FIG. **5**B is a sectional view of an optical device with an optical layer and photoresist layer with a 2D wedge formed therein.

[0016] FIG. **5**C is a sectional view of an optical device having the 2D wedge of FIG. **5**B transferred into the optical layer thereof.

[0017] FIG. **5**D is a sectional view of an optical device with an optical thereon.

[0018] FIG. **5**E is a sectional view of the optical device of FIG. **5**D, with the pattern of the 2D wedge transferred into the underlying optical layer.

[0019] FIG. **6**A is a flowchart showing a method for manufacturing a 2D wedge in an optical device.

[0020] FIG. **6**B is a flowchart showing a method for manufacturing a 2D wedge in an optical device.

[0021] FIG. **7**A is a sectional view of an optical device with an optical layer and encapsulation layer.

[0022] FIG. **7**B is a sectional view of an optical device with an optical layer and encapsulation layer with an opening formed through the encapsulation layer.

[0023] FIG. **8** is a flowchart showing a method for etching an opening in the encapsulation layer of the optical device of FIGS. **7**A and **7**B.

[0024] FIG. **9**A is a sectional view of an optical device with an optical layer and encapsulation layer with a thickness abnormality in a film layer formed thereon.

[0025] FIG. **9**B is a sectional view of an optical device with an optical layer and encapsulation layer having the abnormality thereon removed.

[0026] FIG. **10** is a flowchart showing a method for correcting an abnormality on a material layer of an optical device.

[0027] FIG. **11** is an isometric view of an inkjet etching device.

[0028] FIG. **12**A is a schematic isometric view of a cleaning and drying station.

[0029] FIG. **12**B is a sectional view of an optical device with an optical layer and encapsulation layer formed thereon.

[0030] FIG. **12**C is a sectional view of an optical device with an optical layer and encapsulation layer having a 1D wedge thereon formed.

[0031] FIG. **12**D is an isometric view of the optical device of FIG. **12**C.

[0032] FIG. **13** is schematic representation of an inkjet dispenser.

[0033] FIG. **14** is a flowchart showing a method for etching a 1D wedge on a material layer of an optical device.

DETAILED DESCRIPTION

[0034] Referring initially to FIGS. **1**A, **1**B and **1**C, schematic side sectional views and an isometric view of an optical device **10** with a 2D wedge **11** formed in the encapsulation layer thereof (FIGS. **1**B, **1**C) and useful as a waveguide for use in virtual reality imaging and other applications, is shown. An encapsulation layer **12** extends over and covers an optical layer **19** provided for purposes of receiving light through an incoupler **15** thereof, allowing that light to pass through the optical layer **19**, and pass outwardly of the optical device through an outcoupler **16** thereof, all of which are integrally formed on a substrate **14**. This optical device **10** includes a 2D wedge **11** in the encapsulation layer **12** in the region over the outcoupler **16**, which here is formed using an inkjet wet etching device **1100** (FIG. **11**) to dispense an etchant to selectively, locally, remove material from the encapsulation layer **12** of FIG. **1**A to locally form the 2D wedge extending inwardly from the outer surface thereof over the outcoupler **16** as is shown in FIG. **1**B. The 2D wedge **11** is formed in the encapsulation layer **12** by etching a wedge profile **11***a*, and leaving in place the wedge **11** as a variable thickness region of the encapsulation layer **12** in an area directly over the outcoupler **16**, such that a relatively thick encapsulation layer **12** is present to cover the optical layer **19** to create conditions approximating total internal reflection at the interface of the optical layer **19** and the dielectric layer **12** in regions of the optical layer **19** between the incoupler **15** and the outcoupler **16**, and modifying the transmissive properties and refractive properties of the device by forming the thinner conical feature of the 2D wedge **11** in, or as, a portion of the encapsulation layer **12** overlying the outcoupler **16**.

[0035] To form a 2D wedge **11**, the optical device **10** having a uniform thickness encapsulation layer **12** over an optical layer **19** supported on a substrate **14** thereof as shown in FIG. **1**A is mounted to the moveable stage **1114** of an inkjet etching device **1100** of FIG. **11**. As shown in FIG. **11**, the inkjet etching device **1100** includes a table **1102** supported on, and moveable in the X direction with respect to, a base **1112** thereof, and at least one ink jet type dispenser **1104**, here four such dispensers **1104***a-d*, each configured to dispense droplets **1106** of liquid material therefrom and each having an outlet nozzle **1108***a-d* terminating at a drop dispensing opening **1110***a-d* which faces the table **1102**. The stage **1114** is rotationally coupled to the table **1102**, such as through a shaft (not shown) connected to a stepper or servo motor (not shown) in the table **1102**, and the stage **1114** is rotatable thereby about its center **1116** in the **0** direction of FIG. **11**. To perform wet etching or removal of discrete portions of the encapsulation layer **12** to form the 2D wedge **11** in the desired region of the outwardly facing surface thereof, here over the outcoupler **16** of the device **10**, stage **1114** is positioned below a drop dispensing opening **1110** of an outlet nozzle **1108** of an ink jet dispenser **1104** of the inkjet etching device **1100** with the encapsulation layer **12** facing the inkjet etching device outlet nozzle **1108**, and the stage **1114** is rotated and moved in the X direction to position discrete portions or locations on the encapsulation layer **12** where the 2D wedge **11** is to be formed under the drop dispensing openings **1110** *a-d* of one or more of the inkjet dispensers **1104** *a-d*. The nozzle facing surface of the stage **1114** is located more than the thickness of an optical device **10** from the drop dispensing opening **1010** of the outlet nozzle **1008**, leaving a distance between the drop dispensing opening **1110** and the surface of the encapsulation layer **12** of the optical device **10** on the order of, for example, 2 to 5 mm.

[0036] Here, the optical device **10**, including the optical layer **19** with an incoupler **15** and outcoupler **16** encapsulated by an encapsulation layer **12**, is positioned on the stage **1114** to form the 2D wedge **11** feature, here by etching a concave, generally conical, recess or wedge profile **11***a* into the surface of the encapsulation layer **12** by dispensing droplets **1106** of a wet etching or reactive chemistry onto the encapsulation layer **12** from one or more drop dispensing openings **1110** of the ink jet apparatus **1104** forming a conical outwardly facing surface of the 2D wedge **11**. This wedge profile **11***a* which forms the outwardly facing surface of the 2D wedge **11** is established by causing greater etching to occur where the deepest point of the wedge profile **11***a* is to be formed, and incrementally less etching to occur on the flanking sides thereof, or where the wedge profile **11***a* is in the shape of a cone, incrementally less etching along the flanking portions radially outwardly from the deepest point of the wedge profile **11***a* to the edge of the wedge profile **11***a*. Examples of possible encapsulation layer **12** layer materials into which the 2D wedge profile **11***a* is to be formed, and their appropriately paired etchants include the following pairs; SiO2 material and DHF etchant, Si3N4 material and HF or H3PO4 etchant, TiO2 material and SC1 etchant, a Carbon based material and an organic solvent or a Photoresist remover etchant, and an aSI (amorphous silicon) material using KOH etchant. Etching of the 2D wedge profile **11***a* to form the 2D wedge **11** in a film layer such as the encapsulation layer **12** can be performed in a variety of different ways.

[0037] In one approach or aspect of forming the 2D wedge **11**, droplets **1106** of etchant each having the same or nearly same etchant concentration or molarity is dropped in droplets **1106** from the injection nozzle **1108** in a uniform manner across the area where the 2D wedge **11** is to be formed. As the etchant reacts with the underlying thin film material, here the encapsulation layer **12** on which it was dropped, the etchant is consumed in a reaction with the thin film material. The reaction rate and consumption rate of the etchant are

time related and the etching reaction can be altered or terminated by the addition of quench chemicals. In one aspect, as shown in FIG. **13**, the ink jet dispenser **1104***a* providing etchant to the outlet nozzle **1108***a* thereof is connected to two different feed lines **1118***a* and **1120***a*. Here, first line **1118***a* contains an etchant of uniform concentration or molarity and a uniform concentration quenching chemical is provided in the second line **1120***a*. Each of the first and second lines **1118***a*, **1120***a* includes a valve **1122***a*, **1124***a* selectively opening, and capable of throttling or varying flow therethrough, the flow of the etchant (first line **1118***a*, valve **1122***a*) and quenching chemistry (line **1120***a*, valve **1124***a*) thence flowing into and through the drop dispensing opening **1110***a* of the outlet nozzle **1108***a*. The quenching chemical reacts with the etchant more preferentially than the etchant reacts with the encapsulation material **12**, so that the etchant is consumed by the quenching chemical to stop the etching of the encapsulation layer **12**.

[0038] To create a 2D wedge **11**, i.e., etch the conical wedge profile **11***a* of FIGS. **1**B and **1**C using this ink jet printer **1100**, etchant is released to the outlet nozzle **1108***a* through the first line **1118***a* to cover the entire area where the wedge profile **11***a* is to be formed, and the quenching chemistry is immediately thereafter released to the perimeter of the region where the wedge profile **11***a* profile is being formed. Sequentially deeper areas of the wedge profile **11***a* to be formed located inwardly of the perimeter of the wedge **11** to be formed will receive the quenching chemistry at sequentially later and later times at discrete time intervals between dispensing of the quenching chemistry such that the deepest point of the wedge **11** being formed receives the quenching chemistry last. The locations of the encapsulation layer **12** inwardly of the perimeter of the being-formed wedge profile **11***a* receive the quenching chemistry by movement of the stage **1114** to position discrete areas of the encapsulation layer **12** under the stream of droplets **1106** of the quenching chemistry at a pre-determined time at which the wedge **11**, at that location, has the desired remaining encapsulation layer **12** thickness. Once the entire surface of the wedge profile **11***a* in the encapsulation layer **12** has been quenched, i.e., after a conical wedge profile **11***a* is formed inwardly of the surface thereof, it is then washed by deionized water, dispensed by rinse nozzle **1126** in FIG. **11**, to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. The optical device **10** with wedge formed therein is then removed from the stage **1114** and positioned in a cleaning and drying station **1128** having a spin rinse chuck **1130**. Alternatively, instead of providing two feed lines **1118***a*, **1120***a*, inkjet dispenser **1104***a* may be used to dispense the etchant, and inkjet dispenser **1104***b* is used to dispense the quenching material. Further, to decrease the process time to etch the wedge profile **11***a*, two or more of the inkjet dispensers **1104***a-c* may be used to dispense one or both of the etchant and quenching chemistry, or at least two of the inkjet dispensers **1104***a-d* may be used to dispense etchant, and one or more different ones of the inkjet dispensers **1104***a-d* used to dispense the quenching chemistry.

[0039] In a second aspect, etchant is dispensed in a time or volume varied manner across the wedging area. As the dispensed etchant reacts with the underlying material, the etchant is consumed. To achieve deeper etching of the encapsulation layer **12**, more droplets **1106** (increased density of droplets) are released in deeper etching areas, while fewer droplets **1106** (less droplet density) are released in the shallower regions of the to be formed wedge area, either at relatively the same time, or as etchant is depleted or consumed in the region where the deeper portions of the wedge profile **11***a* are to be formed as compared to shallower to be formed regions thereof. In this aspect, the droplets dispensed by the inkjet dispenser **1104** have a uniform etchant concentration. The etchant reacts with its location of contact with the encapsulation layer **12** until the chemical reaction thereof with the material of the encapsulation layer **12** is exhausted, i.e., until the etchant has been nearly consumed, leaving a limited amount of etching occurring per droplet **1106**. Therefore, in areas with fewer droplets **1106** dispensed, at relatively the same time or over a period of time as etchant is consumed, less etching will occur inwardly of the encapsulation layer **12**, whereas in areas of more droplet release at relatively the same time or over a period of time as etchant is consumed, more etching with occur inwardly of the encapsulation layer **12**. Preferably, the etchant is released in a sequentially, planned, fashion over the surface of the encapsulation layer **12** using the X and Θ motions of the stage **1114** to drop droplets **1106** at locations where the wedge profile **11***a* is to be formed, at a rate no faster than the rate of consumption by the reaction thereof with the encapsulation layer material **12**, wherein the stage **1114** moves the encapsulation layer **12** under the stream of droplets **1106** to selectively replenish the etchant at discrete locales on the encapsulation layer **12**. The area of the encapsulation layer **12** receiving the droplets **1106** of etchant is step wise or continuously reduced, centered at the deepest point of the wedge profile **11***a* being formed inwardly of the encapsulation layer **12**, as the etchant is consumed by reaction with the encapsulation layer **12** material, such that etchant is not dispensed to regions of the wedge profile **11***a* already formed that are shallower than a certain depth, i.e., the regions where the final depth of the wedge profile **11***a* has already been reached by the etching. The stage **1114** initially moves the encapsulation layer **12** under the drop dispensing opening **1110** of the outlet nozzle **1108** to cover the full area where the of the wedge profile **11***a* which defines the outer surfaces of the wedge **11** is to be formed, and then sequentially smaller and smaller areas centered at the deepest locale of the of the wedge profile **11***a*, and the stage eventually stops to position the deepest location of the to be formed wedge profile **11***a* under the last of the droplets **1106** being discharged from the drop dispensing opening **1110** of the outlet nozzle **1108**, to complete etching of the encapsulation layer **12** to form the wedge profile **11***a* and thus the wedge **11** in the encapsulation layer **12**. By this methodology, the portions of the encapsulation layer **12** where the shallower flanks of the wedge profile **11***a* being formed will receive, and be etched by, fewer droplets **1106** of etchant, whereas the portions of the deepest areas of the wedge profile **11***a* being etched into the encapsulation layer **12** receive the most droplets **1106**, and there the encapsulation layer **12** is recessed inwardly the deepest. The surface of the encapsulation layer **12**, including of the just formed wedge **11** outer surface, is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Then, the optical device **10** is removed from the support **1114** and positioned in a cleaning and drying station **1128**. As with the first aspect of forming the wedge profile **11***a*, multiple ones

of the inkjet dispenser's **1104***a-b* may be used to discharge droplets, and thereby potentially reduce the time required to etch the wedge profile **11***a*.

[0040] In a third aspect, etchant to form the wedge profile **11***a* is released in a varied concentration or molarity across the area where the wedge profile **11***a* to define the wedge **11** in the encapsulation layer **12** is to be formed. As the etchant reacts with the underlying material of the encapsulation layer **12**, the etchant is consumed. To achieve deeper etching in desired regions of the encapsulation layer **12**, droplets **1106** having a higher etchant concentration or molarity are released in areas to be deeply etched, while less concentrated droplets (diluted droplets) are released in the areas to be etched less, i.e., the shallower areas of the wedge profile **11***a*. To achieve this, in one aspect the dispenser **1104** providing etchant to the outlet nozzle **1108***a* is connected to two different feed lines **1118***a* and **1120***a*. First line **1118***a* contains an etchant of uniform concentration or molarity and a dilutant, for example deionized water, and is provided in second line **1120***a*. Each of the first and second lines **1118***a*, **1120***a* includes a valve **1122***a*, **1124***a* selectively opening, and capable of throttling or variable flow therethrough, the flow of the etchant (line **1118***a*, valve **1122***a*) and dilutant (line **1120***a*, valve **1124***a*) thence flowing into and through the outlet nozzle **1108***a*. The relative flows of the dilutant and the etchant result in different concentrations of etchant per droplet **1106** dispensed from the drop dispensing opening **1110***a*. The dispensed etchant **1116** reacts with its location of contact with the encapsulation layer **12** until the chemical reaction is exhausted, leaving a limited amount of etching occurring per droplet, with less etching happening where droplets **1106** having lower etchant concentration were dispensed. Etchant droplets **1106** are released in a sequential fashion at a rate no quicker than the rate of consumption thereof by reaction with the encapsulation layer material **12**, wherein the stage **1114** moves and passes the wedge profile **11***a* forming region of the optical device **10** under the inkjet stream **1106**. The portion of the area where the wedge profile **11***a* is to be formed and onto which the etchant is dispensed extends over the full area where the wedge profile **11***a* is to be formed, with the drop dispensing opening **1110***a* of the outlet nozzle **1108***a* releasing droplets **1106** having increasing larger ratios of etchant to dilutant from the location of the perimeter of the area of the encapsulation layer **12** to be etched to the location on the encapsulation layer **12** where the deepest etching into the encapsulation layer **12** to form the wedge profile **11***a* is to occur, at which locale no dilutant will be released with the etchant. Thus, the less deep flanks of the wedge profile **11***a* will receive less concentrated etchant droplets whereas the deepest areas of the encapsulation layer **12** where the wedge profile **11***a* is being formed receive the most concentrated of etchant droplets **1106**, and the wedge profile **11***a* is there etched the deepest. The surface of the encapsulation layer **12** and formed wedge **11** is then washed by deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Then, the optical device **10** is removed from the support **1114** and positioned in a cleaning and drying station **1128**. As with the first and second aspects, multiple ones of the inkjet dispensers **1104***a-b* may be used to discharge droplets of different concentration, and thereby potentially reduce the time required to etch the wedge profile **11***a*. Additionally, one or more of the inkjet dispensers **1104***a-d* may be supplied with the etchant, including etchant of different concentrations, wherein lower concentration droplets **1106** are dispensed to regions of the surface of the encapsulation layer **12** where the variable depth opening is to be shallower, and greater concentration etchant dispensed to regions of the surface of the encapsulation layer **12** where the variable depth opening is to be deeper. In this approach, one of the inkjet dispensers **104***a-d* can dispense a dilutant, which is then mixed with the etchant of different concentrations on different regions of the encapsulation layer, to provide a continuous of nearly continuous change in etchant concentration in the liquid on the encapsulation layer from the areas of the deepest to shallowest portions of the wedge profile **11***a* being formed.

[0041] In a fourth aspect, etchant is released in different size droplets **1106** across the area of the encapsulation layer where the wedge profile **11***a* to form the wedge **11** is to be formed. As the etchant reacts with the underlying material of the encapsulation layer **12**, the etchant is consumed. To achieve deeper etching into the encapsulation layer, larger droplets **1106** are released in deep etching areas, while smaller droplets **1106** are released in the less deep wedge profile **11***a* areas. To achieve this, the inkjet printer **1100** includes an inkjet dispenser **1104** capable of dispensing smaller or larger droplets to be dropped as droplets **1106** dropped through the droplet dispensing opening **1110** of the outlet nozzle **1108**. The etchant reacts with its location of contact with the encapsulation layer **12** until the chemical reaction is exhausted, leaving a limited amount of etching occurring per droplet, with less etching happening where smaller droplets **1106** were dispensed. Here, the viscosity of the droplets is increased to prevent significant movement thereof from their location of placement on the encapsulation layer **12**. Etchant droplets **1106** are released over the entire region of the encapsulation layer **12** where the wedge profile **11***a* to form the wedge **11** is to be formed, in a sequential fashion at a rate no quicker than the rate of consumption of the etchant by the reaction thereof with the encapsulation layer material **12**, wherein the stage **1114** moves the encapsulation layer **12**, and thus different portions of the wedge profile **11***a* being formed to different depths of the optical device **10** thereon under the stream of droplets **1106**. The size of the droplets **1106** is sequentially increased from the perimeter, to the deepest etched location, of the wedge profile **11***a* to be formed. Thus, the shallower flank areas of the wedge profile **11***a* being formed will receive smaller etchant droplets **1106** whereas the deepest areas of the wedge profile **11***a* being formed receive the largest droplets, and the encapsulation layer **12** is therefore etched the deepest at that location. The surface of the encapsulation layer **12** with the wedge **11** formed therein is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Then, the optical device **10** will be removed from the support **1114** and positioned in a cleaning and drying station **1128**.

[0042] As with the first to third aspects of forming the wedge **11**, multiple ones of the inkjet dispensers **1104***a-b* may be used to discharge droplets of different sizes, or each inkjet dispenser **1104** *a-d* of the inkjet dispensers **1104***a-d* is configured to provide droplets within a different subrange of sizes, and thereby potentially reduce the time required to etch the wedge profile **11***a*.

[0043] FIG. **2** is a flowchart showing a series of activities for creating a 2D wedge **11** in an encapsulation layer **12** of an optical device **10** according to the sequence of processes described with respect to FIG. **1**. Initially, an optical layer **19** is prepared. However, the encapsulation layer **12** may need to be of varied thickness to create a desired effect for the optical device **10**, thus the forming of a 2D wedge **11** can be performed. Herein, the process sequence for forming of the 2D wedge in the encapsulation layer **12**, is described.

[0044] At Act **201** the optical device **10** is mounted on the stage **1114** and at Act **203** it is positioned by the stage **1114** within the inkjet wet etching device **1100**, by movement in the X and Θ directions of FIG. **11**, to position the desired locale on the encapsulation layer **12** where the 2D wedge is to be formed below drop dispensing opening **1110** of an outlet nozzle **1108** of an ink jet dispenser **1104**. At Act **205** an etchant capable of reacting with (etching) the material of the encapsulation layer **12** is released from the drop dispensing opening as droplets **1106**. Preferably, this etchant has an etch rate of the material of the optical layer **19** on the order of more than 100 times less than the etch rate for the encapsulation layer **12** when exposed to that same etchant.

[0045] In one aspect, after etchant is released to the outlet nozzle **1108***a* through line **1118***a* to cover the entire area where the wedge profile **11***a* to form the wedge **11** is to be formed, a quenching chemistry is immediately thereafter released to the perimeter of the region where the wedge profile **11***a* is being formed in Act **211**. The locations of the encapsulation layer **12** inwardly of the perimeter of the being-formed wedge profile **11***a* receive the quenching chemistry by movement of the stage **1114** to position discrete areas of the encapsulation layer **12** under the stream of drops **1106** of the quenching chemistry at a pre-determined time at which the wedge profile **11***a*, at that location, has removed sufficient material to form the desired encapsulation layer **12** thickness of the wedge **11** thereat, followed by deeper and deeper areas of the wedge profile **11***a* being formed. Once the entire surface of the wedge profile **11***a* region of the encapsulation layer **12** has been quenched, at Act **221** the surface is then washed by deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. At Act **231** the optical device **10** with the wedge **11** formed therein is then removed from the stage **1114** and positioned in a cleaning and drying station **1128** having a spin rinse chuck **1130** at Act **241** to further rinse, and then dry, the surface of the encapsulation layer **12** with the 2D wedge formed therein.

[0046] In a second aspect, deeper etching is achieved by dispensing more droplets (increased density of droplets) in areas of the wedge profile **11***a* to be formed deeper into the encapsulation layer **12**, while fewer droplets (less droplet density) are released in the shallower regions of the wedge profile **11***a* to be formed in act **205**. Here, the inkjet dispenser **1104** drops droplets **1106** having a uniform etchant concentration to contact the region of the encapsulation layer **12** where the wedge profile **11***a* is to be formed until the chemical reaction is exhausted, i.e., until the etchant has been nearly consumed, leaving a limited amount of etching occurring per droplet. Thereafter, in Act **213**, by movement of the stage **1114** and consequently the encapsulation layer **12** under the stream of droplets **1106**, etchant is selectively replenished at discrete locales on the encapsulation layer **12** here the wedge profile **11***a* is being formed, to further the encapsulation layer **12** in Act **213**, over time, whereby a density variation of droplets over the surface of the region where the wedge profile **11***a* is being formed is achieved. Alternatively, where the droplets **1106** have a relatively high viscosity so as not to significantly move from their location of being dropped on the encapsulation, more droplets **1106** can be dropped in deeper locations of the wedge profile **11***a* to be formed than at shallower regions thereof in a single pass of the wedge profile **11***a* forming region of the encapsulation layer **12** under the drop dispensing outlet **1010**, so that a thicker layer of etchant is present over the deeper locations of the wedge profile **11***a* to be formed than at shallower regions thereof. In Act **223** the surface of the encapsulation layer **12** including the wedge **11** is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed from the support **1114** in act **233** and positioned in a cleaning and drying station **1128** in Act **243** to further rinse, and then dry, the surface of the encapsulation layer **12** with the 2D wedge formed therein.

[0047] In the third aspect, in Act **205** the etchant is released in droplets **1106** of different etchant concentration at different locations of the wedge profile **11***a* being formed. In Act **215**, droplets having a higher etchant concentration or molarity are released in areas of the encapsulation layer **12** to be deeply etched, while less concentrated droplets (diluted droplets) are released in the areas to be etched less, i.e., the shallower locations of the wedge profile **11***a* to be formed. The surface of the encapsulation layer **12** including the wedge **11** is then washed by deionized water in Act **225**, dispensed by rinse nozzle **1126**, to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed in Act **235** from the support **1114** and positioned in a cleaning and drying station **1128** in Act **245** to further rinse, and then dry, the surface of the encapsulation layer **12** with the 2D wedge formed therein.

[0048] In a fourth aspect, as the etchant released in Act **205**, they are released in different size droplets across the area of the encapsulation layer **12** where the wedge profile **11***a* is to be formed. In Act **217**, larger droplets are released in deeper etching areas, while smaller droplets are released in the less deep etching areas, the droplet size modulated by the inkjet dispenser **1104**. The shallower flanks of the wedge profile **11***a* being formed will receive smaller etchant droplets **1106** whereas the deepest areas of the wedge profile **11***a* being formed receive the largest droplets, and the encapsulation layer **12** is therefore etched the deepest at that location. In act **227** the surface of the encapsulation layer **12** with the wedge **11** formed therein is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. In Act **237**, the optical device **10** will be removed from the support **1114** and positioned in a cleaning and drying station **1128** in Act **247** to further rinse, and then dry, the surface of the encapsulation layer **12** with the 2D wedge formed therein.

[0049] Referring now to FIGS. **3**A to **3**C, an additional methodology for forming a photoresist layer for forming a wedge profile, such as that in the optical layer of FIG. **5**E, is shown. Here, the inkjet printer **1100** is used to deposit individual droplets **1106** of a photoresist material to form a photoresist layer **30** on a thin film layer **19***c* present on an

underlying substrate **21**, wherein the formed photoresist layer **30** includes a varying composition over the span thereof, such that a discrete non-uniform portion **23** is formed in the photoresist layer **30** such that the photoresist layer **30**, after being exposed to an electromagnetic energy source such as UV or other source and developed, has a three dimensional feature **31** formed inwardly of the layer of photoresist **30**. Thereafter, by anisotropic etching such as in a plasma etch chamber, the three dimensional profile of the three dimensional recess in the photoresist **30** is transferred into the underlying thin film layer **19***c*, forming a structure similar to the 2D wedge in FIG. **5**E.

[0050] The photoresist material to form the photoresist layer **30** is dispensed in liquid form which is then baked to harden it, for example by including a heater (not shown) under and thermally connected to the stage **1114** of the ink jet apparatus **1100**. Here, the composition of the photoresist layer **30** is changed within to non-uniform region **23** as compared to the remainder of the photoresist of the photoresist layer **30** formed on the thin film layer **19***c*, and is used to form the three dimensional feature **31** in the photoresist layer **30** after it has been exposed to electromagnetic radiation and developed. The composition of the photoresist **30** in the portion of the photoresist **30** deposited in the non-uniform region **23** is also varied across the span or width of the non-uniform region **23**. For example, the polymer, solvent and non-sensitizer additive components of the photoresist material which is dispensed as droplets **1106** by the ink jet apparatus **1100** can remain uniform across the length, width and depth of the photoresist layer formed on the thin film layer **19***c*, but the sensitizer portion of the photoresist, which causes the polymer of the photoresist material to change properties when exposed to the proper electromagnetic energy such as UV light, is non-uniformly included in the photoresist layer **30**, both as between the non-uniform region **23** and the remainder of the photoresist layer **30**, and within the non-uniform region **23** of the photoresist layer **30**.

[0051] To form this non-uniform region, first line **1118***a* of the inkjet dispenser **1104***a* is configured to supply the polymer, solvent and non-sensitizer additive components of the photoresist material, and second line **1120***a* of the inkjet dispenser **1104***a* is configured to supply the sensitizer to the inkjet dispenser **1104** and hence to the outlet nozzle **1108***a*. With the substrate **1102** secured to the stage **1114**, the stage **1114** is moved rotationally about the axis **1116** thereof, and in the X direction using the table **1102** movement, to locate all areas of the upper surface thin film layer **19***c* to face the outlet drop dispensing opening **1010** of the dispense nozzle **1108** to receive the polymer, solvent and non-sensitizer additive components of the photoresist thereon. When the drop dispensing opening **1110** of the outlet nozzle **1108** is facing a portion of the thin film **19***c* over which the non-uniform region **23** is to be formed, valve **1124***a* is also opened to simultaneously flow polymer, solvent and non-sensitizer additive components of the photoresist, along with the sensitizer, onto the thin film layer **19***c*.

[0052] Assuming, for example, that the three dimensional feature **31** is circular in plan view, and has a conical profile extending from the edge **31***a* to the deepest portion **31***b* thereof and similar to the wedge profile **11***a* and 2D wedge **11** shown in FIGS. **1**B and **1**C, with a smooth depth transition from the edge **31***a* to the deepest portion **31***b* thereof. When the surface of the thin film layer **19***c* directly under the drop dispensing opening **1110** is an area where the three dimensional feature **31** is not to be formed, only the polymer, solvent and non-sensitizer additive components of the photoresist are dispensed as droplets **1106**. As the substrate **21** is positioned under the drop dispensing opening **1110** of the outlet nozzle **1108** and the substrate **19***c* is moved to first position the location of the edge **31***a* of the to be formed three dimensional feature **31** directly below the drop dispensing opening **1110**, sensitizer is added to the polymer, solvent and non-sensitizer additive components of the photoresist material being dispensed as droplets **1106** from the drop dispensing opening **1110**. As the stage **1014** moves the substrate **21** to position the deepest portion **31***b* of the to be formed three dimensional feature **31** below the drop dispensing outlet **1110**, more sensitizer is continuously added to the polymer, solvent and non-sensitizer additive components of the photoresist material being dispensed as drops **1106** through the drop dispensing opening **1110***a*, such that the greatest concentration of sensitizer in the mixture of polymer, solvent and non-sensitizer additive and sensitizer of the photoresist being dispensed is present at the deepest location of the three dimensional recess **1214** to be formed, and this concentration is gradually, here generally linearly, reduced as the stage **1114** causes the location of the thin film layer below the opening **1110** to traverse from the deepest **31***b*, to the shallowest (occurring at the edge **31***a*) location of the three dimensional feature **31** to be formed. The resulting photoresist layer **30**, which is electromagnetic energy sensitive only in the region thereof where the sensitizer is present, may be formed in a single pass of all surfaces of the thin film layer **19***c* under the outlet nozzle **1108**, or multiple layers of polymer, solvent and non-sensitizer additive components of the photoresist, and where location appropriate (where the three dimensional feature is to be formed) a gradient of sensitizer, can be dispensed to form the photoresist layer **30**. Here, for example, as the substrate **21** is moved from the deepest portion **31***d* of the non-uniform region **23** of the photoresist layer **30** being formed toward the shallow perimeter **31***a* portion thereof, initially, only at the deepest portion **31***d* is the sensitizer added. Thence, in successive passes of forming the non-uniform region **23** of the photoresist layer **30**, the area extending from the deepest portion **31***d* to the edge **31***a* is successively increased, until in the final pass of droplets **1106** being dispensed, the sensitizer is dispensed over the entire area where the non-uniform portion **23** is formed. Additionally, the photoresist layer **30** can be formed by flowing only the polymer, solvent and non-sensitizer additive components of the photoresist through the inkjet dispenser **1104***a*, and the sensitizer flowed through the adjacent ink jet dispenser **1104***b*. As a result, a photoresist layer having a localized electromagnetic energy sensitive region therein, that localized electromagnetic energy sensitive region having a gradient of sensitivity to electromagnetic energy causing a change in the structure thereof, is formed.

[0053] After the photoresist layer **30**, having the varying concentration of sensitizer region formed therein to form the non-uniform region **23**, is exposed to electromagnetic radiation to which the polymer and sensitizer combination is sensitive, the material properties of the varying sensitizer concentration region are changed so that more of the polymer in the deepest to be formed region of the non-region **23** undergoes a change in property making it more susceptible to being etched, and this increase in etchability is reduced relatively to zero at the edge **31***a* of the to be formed three

dimension feature **31**. The substrate **23** with the exposed photoresist layer is then exposed to a developer, and reacted polymer is dissolved and washed away to yield the three dimensional feature **31** in the photoresist **30** structure of FIG. **12**D.

[0054] Alternatively, where the sensitizer causes the polymer, when exposed to the electromagnetic energy, to be more resistant to being dissolved by the developer, the above described sequence is reversed, and the regions of the photoresist layer being formed where the three dimensional feature **31** will not be present receives the sensitizer, and as the edge **31***a* of the to be formed three dimensional feature **31** becomes present under the drop dispensing opening **1110**, the amount of sensitizer is reduced, such that the closer to the deepest part **31***b* of the two be formed three dimensional feature **31**, the less sensitizer is present, and the lowest concentration, as little as zero, sensitizer is present at the location of the deepest portion **31***b* of the to be formed three dimensional feature **31**.

[0055] Referring to FIG. **4**, a process sequence for forming the three dimensional feature **31** is shown in process flow format. First, at Act **400**, a substrate **23** having the thin film layer **19***c* which may be, for example, an encapsulation layer **12** formed over an optical layer **19** as shown in FIG. **1**, is mounted to the stage **1114** of an inkjet printer **1100**. Then, in Act **402**, the stage is moved to position the thin film layer **19***c* under the droplet dispensing opening **1110** of an inkjet dispenser **1104**. Then while moving the stage in the X and Θ directions, droplets of the photoresist components are released from the droplet dispensing opening **1110** onto the thin film layer **19***c*, such that a gradient in sensitizer is present within the region of the photoresist layer **30** being formed a concave feature is to be formed, in Act **404**. After the full thickness of the photoresist layer is deposited and baked, and in Act the **406** the photoresist is exposed to electromagnetic radiation capable of changing the material properties of the polymer in the photoresist where the sanitizer either is, or is not present, and in Act **408** the exposed photoresist layer **30** is developed. Then, in Act **410**, the developed photoresist layer **30** is rinsed with a solvent which dissolves the polymer and photoresist having the sanitizer (or not having the sanitizer) to form the three dimensional feature **31** inwardly of the layer of photoresist **30**.

[0056] In FIGS. **5**A through **5**C, a schematic side view of the results of a series of processes actions used to create an optical device **10** with a depression **50***a* extending inwardly of the optical layer **19** of the optical device **10**, useful as a waveguide for use in virtual reality imaging and other applications, are shown. In contrast to the method of forming the feature **31** of FIGS. **3** and **4**, where a photoresist layer **30** is formed which includes integrally therein a region having varying photoresist material properties, here the full thickness of a photoresist layer **30** is formed to cover an optical layer **19** and it has continuous material properties across the entire surface thereof. This optical device **10** provided with the photoresist layer **30**, is then exposed to anisotropic etching conditions to transfer a recess or depression **50***a* in the photoresist layer into the underlying optical layer **19** in one strategy as seen in FIGS. **5**A to **5**C and without a photoresist layer in another strategy, as seen in FIGS. **5**D and **5**E where the recess, or depression **50***b*, is formed directly in the optical layer **19** by local inkjet etching thereof. A relatively thick photoresist layer **30** can be used to cover the optical layer **19** of FIG. **5**A to create conditions allowing for a photoresist wedge **50** shown in FIG. **5**B, fabricated by forming the depression **50***a* inwardly of the photoresist **30** of FIG. **5**A, such that the photoresist layer **30** of FIG. **5**B is to be used as a mask for etching the optical layer **19** and transferring the wedge **50** of FIG. **5**B into the optical layer **19** of FIG. **5**C as a transferred optical layer wedge **50***c*.

[0057] To form a 2D photoresist wedge **50** as a portion of the photoresist layer **30**, the optical device **10** having a uniform thickness photoresist layer **30** as shown in FIG. **5**A is mounted to the moveable stage **1114** of an inkjet printer **1100** of FIG. **11**. The printer **1100** here serves as a local, to the photoresist layer **30** surface of the device **10**, dispenser of an etchant or reactant capable of removing or etching away discrete portions of the material of the photoresist layer **30**. The printer includes a table **1102** supported on, and moveable in the X direction with respect to, a base **1112** thereof, and at least one ink jet type dispenser **1104**, here four such dispensers **1104***a-d*, each configured to dispense droplets **1106** of liquid material therefrom, and each having an outlet nozzle **1108** which selectively faces the table **1102**. The stage **1114** is rotationally coupled to the table **1102**, such as through a shaft (not shown) connected to a stepper motor (not shown) in the table **1112**, and the stage **114** is rotatable about its center **1116** in the **0** direction of FIG. **11**. To perform etching of the photoresist layer **31** to form the 2D photoresist wedge **50**, here having a topography similar to the conical 2D wedge **11** of FIGS. **1**B and **1**C, in the desired region thereof, stage **1114** is positioned below the outlet **1108** of the ink jet dispenser **1104** of the inkjet etching device **1100** with the photoresist layer **30** side of the device **10** facing the drop dispensing outlet **1110** of the outlet nozzle **1108**, and the stage **1114** is rotated and moved in the X direction to position discrete portions of the location on the device **10** where the 2D photoresist wedge **50** is to be formed under the drop dispensing outlet **1100** of an outlet **1108** of one or more inkjet dispensers **1104***a-d*. The nozzle facing surface of the stage **1114** is located more than the thickness of an optical device **10** from the drop dispensing opening **1010** of the outlet nozzle **1008** exit of the inkjet nozzle, leaving a distance between the nozzle exit and the surface of the photoresist layer **30** of the optical device **10** on the order of 2 to 5 mm.

[0058] Here, the optical device **10**, covered by a photoresist layer **30**, is positioned on the stage **1114** to form the 2D photoresist wedge **50** into the extant photoresist layer **30** of FIG. **5**A by etching a depression **50***a* inwardly of the outer surface of the photoresist layer **30**, by dispensing droplets **1106** of a wet etching or reactive chemistry onto the photoresist layer **30** from one or more outlets **1108** of an ink jet dispenser **1104**, the resulting depression **50***a* shown in FIG. **5**B. The profile of the depression is established by causing greater etching to occur where the deepest point of the depression **50***a* is to be formed, and incrementally causing less etching to occur on the flanking sides extending from the deepest portion of the to be formed depression **50***a*, or where a circular region, flanking portions extending radially outwardly from the deepest point of the depression **50***a* to be formed. An example of the material of the photoresist layer **30** layer its appropriately paired etchants include a Carbon based material and an organic solvent or a photoresist

remover etchant. Etching of the depression **50***a* into the photoresist layer **30** can be performed in a variety of different ways.

[0059] In one approach or aspect of forming the depression **50***a*, etchant having the same etchant concentration or molarity is dropped in droplets **1106** from the injection nozzle **1108** in a uniform manner across the area where the depression **50***a* to form the photoresist wedge **50** is to be formed. As the etchant reacts with the underlying photoresist **30** on which it was dropped, the etchant is consumed in a reaction with the photoresist **30**. The reaction rate and consumption rate of the etchant are time functions and the total amount of photoresist locally etched away can be altered by the addition of quench chemicals. In one aspect, as shown in FIG. **13**, the inkjet dispenser **1104***a* providing etchant to the outlet nozzle **1108***a* is connected to two different feed lines **1118***a* and **1120***a*. First line **1118***a* contains an etchant of uniform concentration or molarity and a uniform concentration quenching chemical is provided in second line **1120***a*. Each of the first and second lines **1118***a*, **1120***a* includes a valve **1122***a*, **1124***a* selectively opening, and capable of throttling or varying flow therethrough, the flow of the etchant (line **1118***a*, valve **1122***a*) and quenching chemistry (line **1120***a*, valve **1124***a*) then flowing into and through the drop dispensing outlet **1110***a* of the outlet nozzle **1108***a*. The quenching chemical reacts with the etchant more preferentially than the etchant reacts with the photoresist layer **30**, so that the etchant is consumed by the quenching chemical to stop the etching of the photoresist layer **30**.

[0060] To create a photoresist wedge **50** using this system, etchant is released to the outlet nozzle **1108***a* through line **1118***a* to cover the entire area where the photoresist wedge **50** is to be formed, and the quenching chemistry is immediately thereafter released to the location of the perimeter of the depression **50***a* is being formed. Sequentially deeper areas of the depression **50** to be formed located inwardly of the perimeter of the depression **50** to be formed will receive the quenching chemistry at sequentially later and later times at discrete time intervals between the dispensing of the quenching chemistry until the deepest point of the depression **50***a* being formed receives the quenching chemistry. The locations of the photoresist layer **30** inwardly of the perimeter of the being-formed depression **50***a* receive the quenching chemistry by movement of the stage **1114** to position discrete areas of the photoresist layer **30** under the stream of droplets **1106** of the quenching chemistry at a pre-determined time based on the desired depth of the depression **50***a* at that location, such that the desired photoresist layer **30** thickness to provide the photoresist wedge **50** remains. Once the entire surface of the depression **50** of the photoresist layer **30** has been quenched, the photoresist **50** surface is then washed with a neutral liquid such as deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. The optical device **10** with the photoresist wedge **50** formed therein is then removed from the stage **1114** and positioned in a cleaning and drying station **1128** having a spin rinse chuck **1130** to be further cleaned and dried.

[0061] In a second aspect of fabricating the photoresist wedge **50**, etchant is dispensed in a time varied manner across the area where the depression **50***a* is to be formed. As the dispensed etchant reacts with the underlying material, the etchant is consumed. To achieve deeper etching of the photoresist layer **30** in selected portions thereof, more droplets **1106** (increased density of droplets) are released in deeper etching areas, while fewer droplets (less droplet density) are released in the shallower regions where the depression **50***a* is to be formed. In this aspect, the inkjet dispenser **1104** droplets **1106** have a uniform etchant concentration. The etchant reacts with the photoresist at its location of contact with the photoresist layer **30** until the chemical reaction is exhausted, i.e., until the etchant has been nearly consumed, leaving a limited amount of etching occurring per droplet. Therefore, in areas with fewer droplets, less etching will occur inwardly of the photoresist layer **30**, whereas in areas of more droplet release, more etching with occur inwardly of the photoresist layer **30**. Etchant is released in a sequentially planned fashion at a rate no faster than the rate of consumption by the reaction thereof by reaction with the photoresist layer **30**, wherein the stage **1114** moves the photoresist layer **30** under the stream of droplets **1106** to selectively replenish the etchant at discrete locales on the photoresist layer **30**, with more droplets **1106** dispensed in regions where the depression **50***a* is to be formed deeper into the photoresist **30**, and fewer droplets dispensed in regions where the depression **50***a* is to be formed shallower into the photoresist **30**, with the greatest number of droplets **1106** dispensed over the region where the depression **50***a* is to be deepest, and the fewest at the perimeter of the depression **50***a* where the depression is to be the shallowest. The stage **1114** initially moves the photoresist layer **30** under the outlet nozzle **1108** to cover the full area where the depression **50***a*, and thus the wedge **50**, is to be formed, and sequentially smaller and smaller areas centered at the deepest locale of the to be formed depression **50***a* receive the etchant, and the stage eventually stops to position the drop dispensing outlet **1110** over the deepest location of the to be formed depression **50***a* to there dispense additional droplets **1106** of etchant, to complete etching of the photoresist layer **30** to form the wedge **50**. By this methodology, the portions of the photoresist layer **30** where the shallower flank portions of the wedge **50** depression **50***a* are being formed will receive, and be etched by, fewer droplets of etchant, whereas the deepest areas of the depression **50***a* to be formed inwardly of the photoresist layer **30** receive the most droplets **1106**, and there the photoresist layer **30** is recessed the deepest. The surface of the photoresist layer **30**, including of the wedge **50**, is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed from the support **1114** and positioned in a cleaning and drying station **1128** to be further cleaned and dried.

[0062] In a third aspect, etchant is released in a varying concentration or molarity across the area where the wedge **50**, and thus depression **50***a*, is to be formed. As the etchant reacts with the underlying material of the photoresist layer **30**, the etchant is consumed. To achieve deeper etching in desired regions of the photoresist layer **30** etchant droplets **1106** having a higher etchant concentration or molarity are released in areas to be deeply etched, while less concentrated droplets (diluted droplets) are released in the areas to be etched less, i.e., the shallower depression **50***a* areas. To achieve this, the inkjet dispenser **1104** providing etchant to the outlet nozzle **1108***a* is connected to two different feed lines First line **1118***a* contains an etchant of uniform concentration or molarity and dilutant, for example deionized

water, is provided in second line **1120***a*. Each of the first and second lines **1118***a*, **1120***a* includes a valve **1122***a*, **1124***a* selectively opening, and capable of throttling or variable flow therethrough, the flow of the etchant (line **1118***a*, valve **1122***a*) and dilutant chemistry (line **1120***a*, valve **1124***a*) and flowing into and through the drop dispensing opening **1110***a* of the outlet nozzle **1108***a*. The relative flow of the dilutant and the etchant result in different concentrations of etchant per drop let **1006**. The dispensed etchant **1116** reacts with the location of contact thereof with the photoresist layer **30** until the chemical reaction is exhausted, leaving a limited amount of etching occurring per droplet **1006**, with less etching happening where droplets **1006** having lower etchant concentration were dispensed. Etchant is released in a sequentially planned fashion at a rate no quicker than the rate of consumption by the photoresist layer **30** material **12**, wherein the stage **1114** moves the optical device **10** under the stream of droplets **1106**. The area onto which the etchant is dispensed extends over the full area where the photoresist wedge **50**, and thus depression **50***a*, is to be formed, with the drop dispensing outlet **1110** of the outlet nozzle **1108***a* releasing droplets **1106** having increasing larger ratios of etchant to dilutant from the location of the perimeter of the area of the photoresist layer **30** to be etched to the location on the photoresist layer **30** where the deepest etching into the photoresist layer **30***s* to occur, at which locale no dilutant with be released with etchant. Thus, the shallower flanks of the depression **50***a* will receive less concentrated etchant droplets **1106** whereas the deepest areas of the to be formed depression **50***a* in the photoresist layer **30** where the photoresist wedge **50** is being formed receive the most concentrated droplets **1106**, and is therefore etched the deepest. The surface is then washed by deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** removed from the support **1114** and positioned in a cleaning and drying station **1128** to be cleaned and dried.

[0063] In a fourth aspect, etchant is released in different size droplets across the area of the photoresist layer **30** where the photoresist wedge **50** is to be formed. As the etchant reacts with the underlying material of the photoresist layer **30**, the etchant is consumed. To achieve deeper etching into the photoresist layer **30**, larger droplets are released in deep etching areas, while smaller droplets are released in the less deep wedge area. To achieve this, the inkjet printer **1100** includes an inkjet dispenser **1104** capable of dispensing smaller or larger droplets to be dropped as droplets **1106** through the drop dispensing outlet **1010** of the outlet nozzle **1108**. The etchant reacts with the location of contact with the photoresist layer **30** until the chemical reaction is exhausted, leaving a limited amount of etching occurring per droplet, with less etching happening where smaller droplets **1106** were dispensed. Here, preferably a higher viscosity material as the etchant, or a carrier for the etchant, is employed, to reduce flowing of the etchant away from the location on the photoresist where it was dispensed, such that a thicker layer of etchant can be present over the deepest part of the to be formed depression tapering in thickness to the thinnest portion of etchant present at the location of the perimeter of the to be formed depression **50***a*. The size of the droplets **1106** is sequentially increased from the perimeter, to the deepest to be etched location, of the depression **50***a* to be formed. Thus, the shallower flanks of the area where the depression **50***a* being formed will receive smaller etchant droplets **1106** whereas the deepest areas of the depression **50***a* to be formed receive the largest droplets, and the photoresist layer **30** is therefore etched the deepest at that location. The surface of the photoresist layer **30** with the wedge **50** formed therein is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed from the support **1114** and positioned in a cleaning and drying station **1128** to be cleaned and dried.

[0064] As a result, an optical device **10** having a flat optical layer **19** with a photoresist layer **30** with a 2D wedge **50***c* therein can be used to form a 2D wedge **50***c* in the optical layer **19** thereof as shown in FIG. **5**C. The photoresist layer **30** is used as a masking pattern for an anisotropic plasma etch of the device to transfer the profile of the wedge **50** into the optical layer as optical layer wedge **50***b* as shown in FIG. **5**C. This reactive ion etch removes both the photoresist layer **30** and the optical layer **19** material, such that the wedge **50***c* pattern is etched into the optical layer **19** as shown in FIG. **5**C. The variation in thickness created by the 2D wedge **50** in the photoresist **30** allows for more etching of the optical layer **19** to occur under the locales where there is less thickness of photoresist **30**, i.e., in the deeper areas of the recess **50***a*, and less etching to occur in the optical layer under the more thickly covered areas thereof, i.e., in the shallower areas of the recess **50***a* and the non-recessed areas of the photoresist **30**. The resulting etch transfers the pattern of the wedge **50** in the photoresist into the optical layer **19**, resulting in an optical device **10** with a 2D optical layer wedge **50***c* in the optical layer **19**. Any residual photoresist layer **30** is then removed by etching, and the resulting device is cleaned, such as by a wet clean process.

[0065] In FIGS. **5**D and **5**E, a schematic side view of a device **10** for illustrating a different series of actions to fabricate an optical device **10** with a 2D optical layer wedge **50***b* within the optical layer **19** of the optical device **10**. This optical device **10** is not provided with a photoresist layer **30**. In this aspect of the formation of the optical layer wedge **50***b* into the optical layer **19**, any of the four aspects of the process of forming the feature as described with respect to FIGS. **5**A-C are used, except the material being etched is the underlying waveguide material, and the etchant is specific to the waveguide material.

[0066] FIG. **6**A is a flowchart showing a series of activities for creating a 2D optical layer wedge **50***b* in an optical layer **19** of an optical device **10** according to the sequence of processes described with respect to FIGS. **5**A-C. Initially, an optical layer **19** coated with a photoresist layer **30** by flowable chemical vapor deposition, physical vapor deposition, spin coating or other deposition paradigm, is prepared, a wedge **50** is formed in the photoresist **30**, and that wedge **50** pattern is transferred into the underlying optical layer **19**.

[0067] At Act **601** the optical device **10** comprising of an optical layer **19** with a photoresist layer **30** is positioned or mounted on the stage **1114** within the inkjet wet etching device **1100**, and the stage moved in the X and Θ directions of FIG. **11** to position the desired locale on the photoresist **30** where the wedge **50** is to be formed beneath the drop dispensing opening **1010** of the outlet nozzle **1008** of the inkjet printer in Act **603**. At Act **605** an etchant capable of reacting with (etching) the material of the photoresist layer **30** is released from the drop dispensing opening. Specifi-

cally this etchant has an etch rate of the material of the optical layer **19** on the order of more than 100 times less than the etch rate for the photoresist layer **30** exposed to that same etchant.

[0068] The optical device **10** having the photoresist layer **30** layer thereon, is positioned on the stage **1114** to form the photoresist wedge **50** bounded by the surface of the depression **50***a* extending inwardly of the outer surface of the photoresist layer **30**, by dispensing droplets **1106** of a wet etching or reactive chemistry onto the photoresist layer **30** from one or more outlets **1108** of an ink jet apparatus **1104**. The wedge or depression **50***a* profile is established by causing greater etching to occur where the deepest point of the depression **50***a* is to be formed, and incrementally less etching to occur on the flanking side thereof, or where a circular region flanking portions radially outwardly from the deepest point of the depression **50***a*.

[0069] In one approach or aspect, etchant having the same etchant concentration or molarity is dropped in droplets **1106** from the injection nozzle **1108** in a uniform manner across the area where the wedge **50** is to be formed in Act **605**, and a quenching chemistry is immediately thereafter released to the perimeter of the region where the wedge is being formed, and then sequentially onto additional regions of the surface of the photoresist **30**, until the quenching chemistry is released over the deepest portion of the recess **50***a* to be formed, in Act **611**. Once the surface of the photoresist layer **30** has received the quenching chemistry and the etch reaction has been quenched, at Act **621** the surface of the photoresist **30** is then washed with a neutral solution, such as by deionized water to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. At Act **631** the optical device **10** with the wedge **50** formed in the photoresist **30** thereon is then removed from the stage **1114** and dried in a cleaning and drying station **1128** at Act **641** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0070] In a second aspect, the profile of the depression **50***a* is achieved by dispensing more droplets **1106** (increased density of droplets) areas of the photoresist layer **30** to be etched deeper, while fewer droplets **1106** (less droplet density) droplets **1106** having a uniform etchant concentration are released to contact on the photoresist layer **30** until the chemical reaction is exhausted, and in areas with fewer droplets, less etching will occur inwardly of the photoresist layer **30**, whereas in areas of more droplet release, more etching with occur inwardly of the photoresist layer **30**, the positioning of the droplets **1106** achieved by movement of the stage **1114** and consequently the photoresist layer **30** under the stream of droplets **1106** to selectively replenish the etchant at discrete locales on the photoresist layer **30**. Once the depression **50***a* is formed, in Act **623** the surface of the photoresist layer **30**, including of the wedge **50**, is washed with a neutral such as deionized water to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Thereafter, the optical device **10** is removed from the support **1114** in act **633** and positioned in, and cleaned in, a cleaning and drying station **1128** in Act **643** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0071] In a third aspect, etchant is released in a varied concentration or molarity across the area where the depression **50***a* in the photoresist layer **30** is to be formed. In Act **615**, droplets having a higher etchant concentration or molarity are released in areas of the photoresist layer **30** to be deeply etched, while less concentrated droplets (diluted droplets) are released in the areas to be etched less, i.e., the shallower deep wedge areas. The surface of the photoresist **30** having the depression **50***a* formed therein is then washed by a neutral, such as deionized water in Act **625** Then the optical device **10** is removed in Act **635** from the support **1114** and positioned in, and cleaned in, a cleaning and drying station **1128** in Act **645** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0072] In a fourth aspect, etchant is released in different size droplets across the area of the photoresist layer **30** where the wedge **50***c* is to be formed. In Act **617**, larger droplets are released in deep etching areas of the depression **50***a* being formed, while smaller droplets (diluted droplets) are released in the shallower regions of the depression **50***a* being form to yield the wedge **50***c*, the size of the droplets **1106** modulated by the ink jet dispenser **1104** in the outlet nozzle **1108**. The shallower flanks of the area where the depression **50***a* is being formed will receive smaller etchant droplets **1106** whereas the deepest areas of the depression **50***a* being formed receive the largest droplets, and the photoresist layer **30** is therefore etched the deepest at that location. In act **627** the surface of the photoresist layer **30** with the photoresist wedge **50** formed therein is then washed by deionized water to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. In Act **637**, the optical device **10** is removed from the support **1114** and positioned in, and cleaned in, a cleaning and drying station **1128** in Act **647** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0073] Thus, a resulting optical device **10** with a flat upper surface of the optical layer **19** with a photoresist layer **30** with a wedge **50** therein is formed. At this point, the shape of the wedge **50***c* in the photoresist layer **30** is transferred into the underlying optical layer **19**, using the photoresist layer as a mask for anisotropic plasma etching of apportion of the optical layer to transfer form a corresponding wedge **50***b* therein in Act **650**.

[0074] FIG. **6**B is a flowchart showing a series of activities for creating the wedge **50***b* directly into the optical layer **19** of an optical device **10** according to the sequence of processes described with respect to FIG. **1**. Initially, an optical layer **19** of uniform thickness is prepared.

[0075] Here, an optical device **10** having an exposed, i.e., at least a portion thereof is not covered by another film layer, is provided in Act **661**, and is positioned on the stage **1114** within the inkjet wet etching device **1100**, and the stage moved in the X and Θ directions of FIG. **11** to position the desired locale on the device **10** where the 2D wedge **50***b* is to be formed therein below the inkjet outlet nozzle **1008**, in Act **663**. At Act **665** an etchant capable of reacting with (etching) the material of the optical layer **19** is released from the dispense nozzle.

[0076] Here, the wedge is directly etched into the exposed surface of the optical layer **19**. Examples of possible optical layer **19** layer materials and their appropriately paired etchants include the following pairs; SiO2 material and DHF etchant, Si3N4 material and HF or H3PO4 as etchant, TiO2 material and SC1 etchant, a Carbon based material and an organic solvent or a photoresist remover etchant, and an aSI

(amorphous silicon) material using KOH etchant. Etching of the depression to form the optical layer **50***b* can be performed in a variety of different ways.

[0077] In one approach or aspect, after he substrate is provided in Act **601**, and mounted on the stage **1114** and the region where the 2D wedge **50***b* is to be formed is positioned under the drop dispensing outlet **1110** of an outlet nozzle **1108** of an inkjet dispenser **1104** in Act **663**, etchant having the same etchant concentration or molarity is dropped in droplets **1106** from the injection nozzle **1108** in a uniform manner across the area where the depression forming the optical layer wedge **50***b* is to be formed in Act **605**. In Act **665** etchant is released to the outlet nozzle **1108***a* through first line **1118***a* to cover the entire area where the optical layer wedge **50***b* is to be formed, and the quenching chemistry is immediately thereafter released to the perimeter of the region where the optical layer wedge **50***b* is being formed in Act **671**. The locations of optical layer **19** inwardly of the perimeter of the being-formed optical layer wedge **50***b* receive the quenching chemistry by movement of the stage **1114** to position discrete areas of the optical layer **19** under the stream of drops **1106** of the quenching chemistry at a pre-determined time at which the optical layer wedge **50***b*, at that location, has the desired optical layer **19** thickness. Once the entire surface of the region of the optical layer **19** where the optical layer wedge **50***b* is being formed has been quenched, at Act **681** the surface is then washed by a neutral, such as deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. At Act **691** the optical device **10** with wedge formed therein is then removed from the stage **1114** and positioned in a cleaning and drying station at Act **692 1128** having a spin rinse chuck **1130** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0078] In a second aspect, to form the optical layer wedge **50***b*, regions thereof to be formed requiring deeper etching, this achieved by dispensing more droplets (increased density of droplets) onto the optical layer **19** at those locations, while fewer droplets (less droplet density) are released onto the optical layer **19** in the shallower regions of the to be formed optical layer wedge **50***b*. In Act **673**, the inkjet dispenser **1104** droplets having a uniform etchant concentration are released to contact the optical layer **19** until the chemical reaction between the droplet chemistry and the optical layer is exhausted, and in areas with fewer droplets, less etching will occur inwardly of the optical layer **19**, whereas in areas of greater droplet release, more etching with occur inwardly of the optical layer **19** In Act **683** the surface of the optical layer **19**, including of the just formed optical layer wedge **50***b*, is then washed by a neutral, such as deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Then, the optical device **10** is be removed from the support **1114** in act **693** and positioned in a cleaning and drying station **1128** in Act **694** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0079] In a third aspect, etchant is released in a varied concentration or molarity across the area where the optical layer wedge **50***b* is to be formed. In Act **675**, droplets having a higher etchant concentration or molarity are released in areas of the optical layer **19** to be deeply etched, while less concentrated droplets **1106** (diluted droplets) having a lower content of the etchant or reactant therein are released in the areas to be etched less, i.e., the shallower optical layer wedge **50***b* areas. The surface of the optical layer **19** now including the wedge **50***b* is then washed by a neutral such as deionized water in Act **685**, dispensed by rinse nozzle **1126**, to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. Then, the optical device **10** will be removed in Act **695** from the support **1114** and positioned in a cleaning and drying station **1128** in Act **696** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0080] In a fourth aspect, etchant droplets having different sizes and the same reactant or etchant concentration therein are released in different portions of the area of the optical layer **19** where the optical layer wedge **50***b* is to be formed. In Act **677**, larger droplets are released in deep etching areas, while smaller droplets are released in the less deep 2D wedge **50***b* area, the drop size being modulated by the inkjet dispenser **1104**. The shallower flanks of the area where the depression forming a wedge is being formed will receive smaller etchant droplets **1106** whereas the deepest areas of the depression being formed to create an optical layer wedge **50***b* receive the largest droplets, and the optical layer **19** is therefore etched the deepest at that location. In act **687** the surface of the optical layer **19** with the optical layer wedge **50***b* formed therein is then washed by a neutral, such as deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. In Act **697**, the optical device **10** is removed from the support **1114** and positioned in a cleaning and drying station **1128** in Act **698** to further rinse, and then dry, the surface of the photoresist layer **30** with the 2D wedge **50***c* formed therein.

[0081] Referring to FIGS. **7**A and **7**B, a schematic side view of an optical device **10** with an overlying encapsulation layer **12** (FIG. **7**A) portion and an open portion **71** of the encapsulation layer **12** formed by selectively removing a portion of the encapsulation layer by ink jet etching (FIG. **7**B) is shown, the device **10** useful as a waveguide for use in virtual reality imaging and other applications as discussed previously herein. Here, the optical device **10** includes the open portion **71** of the encapsulation layer **12** over the incoupler **15**, which open portion **71** here is formed using an inkjet dispenser **1004** to dispense an etchant to selectively, locally, remove material from the encapsulation layer **12** to locally form the open portion **71** of the encapsulation layer **12** and expose the optical layer **19** therebelow.

[0082] To form the open portion on the surface of the encapsulation layer **12**, the optical device **10** having a uniform thickness encapsulation layer **12** as shown in FIG. **7**A is mounted to the moveable stage **1114** of an inkjet printer **1100** of FIG. **11**. To perform etching of the dielectric encapsulation layer **12** to form the opening **71** in the desired region thereof, here over the incoupler **15**, stage **1114** is positioned below the drop dispensing outlet **1110** of the ink jet dispenser **1104** with the encapsulation layer **12** side of the device table facing the inkjet etching device outlet nozzle **1108**, and the stage **1114** is rotated and moved in the X direction to position discrete portions of the location on the device **10** where the opening **71** is to be formed under the drop dispensing outlet **1110** of one or more inkjet dispensers **1104**. The outlet **1108** nozzle facing surface of the stage **1114** is located more than the thickness of an optical device **10**

from the drop dispensing opening **1010** of the outlet nozzle **1008** exit of the inkjet nozzle, leaving a distance between the nozzle exit and the surface of the encapsulation layer **12** of the optical device **10** on the order of 2 to 5 mm.

[0083] Here, as the opening **71** in the encapsulation layer exposes the underlying optical layer **19** within the perimeter thereof, the reactant or etchant to remove the encapsulation layer material should be very highly selective to etch the encapsulation layer, and the material forming the optical layer **19**. Here, the in coupler **15** of the optical layer **19** has a grating of nano pillars **19***a* within regions **19***b* of the encapsulation layer **12** material extending therebetween. Thus, the portions **19***b* will be, or can selectively be, removed when the overlying portion of the encapsulation layer **12** is removed. Examples of possible encapsulation layer **12** layer materials and their appropriately paired etchants useful to form the opening **71** include the following pairs; SiO2 material and DHF etchant, Si3N4 material and HF or H3PO4 as etchant, TiO2 material and SC1 etchant, a Carbon based material and an organic solvent or a photoresist remover etchant, and an aSI (amorphous silicon) material using KOH etchant. Etching of the gap **71** can be done in a film layer and can be performed in a variety of different ways.

[0084] To form the opening **71**, the underlying material of the optical layer **19** and the substrate **21** on which the optical layer **19** is provided serve as etch stop layers, i.e., as the etchant is selective to etch the encapsulation material highly preferentially to etching the substrate **21** and optical layer **19** materials, such that the encapsulation layer **12** over the incoupler **15** and the regions **19***b* therein are removed without deleterious effects on the gratings **19***b* or the outer surface of the optical layer **19**.

[0085] To form the opening **71**, etchant is dropped from the drop dispensing outlet **1010** of the inkjet dispenser **1104** uniformly over the entire region where the opening **71** is to be formed, and is allowed to etch through the encapsulation layer **12** over the incoupler **15** and also, if desired, remove the portions **19***b* in the incoupler **15** by continuing to allow the etchant to etch or by adding additional droplets **1106** of etchant once the surface of the optical layer **19** is exposed. Once etching is complete, here with the result shown in FIG. **7**B where the portions **19***b* of the incoupler **15** removed, the reaction may be quenched, such as by supplying a quenching chemical through second line **1120***b* of FIG. **13** where the etchant was supplied through line **1120***a*, to be dispensed through the drop dispensing outlet **1110** of the inkjet dispenser **1104** to neutralize the etchant and thereby stop the etching, or, the surface can be rinsed with a neutral, such as deionized water dispensed from rinse nozzle **1126**, to remove the etchant and stop the removal process. A quenching chemical may also be dispensed from the rinse nozzle **1126**. When washed with the neutral liquid from the rinse nozzle, the liquid removes etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. The optical device **10** with gap **71** formed therein is then removed from the stage **1114** and positioned in a cleaning and drying station **1128** having a spin rinse chuck **1130** to be further cleaned and dried. Alternatively, once the opening **71** is formed but the regions **19***b* of the encapsulation material remain, the inkjet apparatus **1100** can be controlled to dispense droplets **1106** of etchant only onto the upper surface of the regions **19***b*, rather over the entire opening **71** area, to remove these regions **19***b* of encapsulation material.

[0086] FIG. **8** is a flowchart showing a series of activities for creating the opening gap **71** in the encapsulation layer **12** over an optical layer **19** of an optical device **10** according to the sequence of processes described with respect to FIG. **7**.

[0087] Initially, an optical layer **19** coated with an encapsulation layer **12** is positioned on the stage **1114**, with the encapsulation layer **12** facing upwardly in Act **801**. Then in Act **803**, the stage **1114** is moved to position the desired location for where the opening **71** is to be formed through the encapsulation layer **12** below the drop dispensing outlet **1110** of an inkjet dispenser **1104**. Thereafter, several different strategies may be taken to create the desired opening **71** in the encapsulation layer **12**.

[0088] In one embodiment, etchant droplets **1106** of uniform size and etchant concentration are released over the entire surface of the encapsulation layer **12** including where the opening **71** is desired to be formed in Act **805**. In Act **811** quenching chemical is released in the locations of the encapsulation layer that the etchant has reached but where the opening **71** is not desired. When opening depth is reached, i.e., when the upper layer of the optical layer **19** is exposed, etching is terminated in Act **821**, such as by supplying a quenching chemistry on the exposed optical layer **19** in the opening **71** and adjacent portions of the encapsulation layer **12**, supplying a rinsing liquid such as deionized water to wash away the etchant, or a combination thereof. Then, in Act **831**, the device is moved to a cleaner and cleaned and dried in Act **841**.

[0089] In another embodiment, etchant droplets of uniform size and etchant concentration are released exclusively at the location of the encapsulation layer **12** in which the opening **71'** is desired in Act **813**. When opening depth through the encapsulation layer **12** is reached to expose the optical layer **19** therein—etching is terminated in Act **823**, such as by supplying a quenching chemistry on the exposed optical layer **19** in the opening **71** and adjacent portions of the encapsulation layer **12**, supplying a rinsing liquid such as deionized water to wash away the etchant, or a combination thereof. Then, in Act **833**, the device is moved to a cleaner and cleaned and dried in Act **843**.

[0090] In another embodiment, buffer droplets of uniform size, density, and concentration are released over the entirety of the optical device **10** except for at the location of the encapsulation layer **12** in which the opening **71'** is desired in Act **807**. In Act **815** droplets having a constant concentration of the etchant therein are released over the entirety of the encapsulation layer **12**, or at least portions thereof greater than the region of the opening **71** being formed. When opening depth is reached, i.e., when the optical layer **19** is exposed in the opening **71**, etching is terminated in Act **825**, such as by supplying a quenching chemistry on the opening **71** and adjacent portions of the encapsulation layer **12**, supplying a rinsing liquid such as deionized water to wash away the etchant, or a combination thereof. Then, in Act **835**, the device is moved to a cleaner and cleaned and dried in Act **845**.

[0091] Referring to FIGS. **9**A and **9**B, a schematic side view of an optical device **10** with an abnormality in thickness of or in a film layer thereon, (FIG. **9**A) and a smoothed abnormality in thickness of the encapsulation layer (FIG. **9**B) is shown. The optical device **10** in FIG. **9**A includes an

abnormality in thickness **91** in the encapsulation layer **12**, which here is corrected using an inkjet wet etching device **1100** to dispense an etchant to selectively, locally, remove material from the encapsulation layer to locally form the smooth and level surface of the encapsulation layer **12** of FIG. **9**B.

[0092] To correct the abnormality in thickness, here an abnormality **91**, or undesired extension of the encapsulation layer **12** above the desired upper plane thereof which extends on the surface of the encapsulation layer **12**, the optical device **10** having the abnormality **91** is mounted to the moveable stage **1114** of an inkjet printer **1100** of FIG. **11**. The printer **1100** here serves as a local, to the encapsulation layer **12** surface of the device **10**, dispenser of an etchant or reactant capable of removing or etching away discrete portions of the material of the encapsulation layer **12**. The printer includes the table **1102** supported on, and moveable in the X direction with respect to, a base **1112** thereof, and at least one ink jet type dispenser **1104**, here four such dispensers **1104***a-d*, each configured to dispense droplets **1106** of liquid material therefrom, and each having an outlet nozzle **1108** which selectively faces the table **1102**. The stage **1114** is rotationally coupled to the table **1102**, such as through a shaft (not shown) connected to a stepper motor (not shown) in the table **1112**, and the stage **114** is rotatable about its center **1116** in the **0** direction of FIG. **11**. To perform etching of the dielectric encapsulation layer **12** to remove the thickness abnormality **91** in the desired region thereof, here over the thickness abnormality **91** of the device **10**, stage **1114** is positioned below the outlet **1108** of the ink jet dispenser **1104** of the drop dispensing outlet **1110** of the inkjet etching device **1100** with the encapsulation layer **12** side of the device table facing the inkjet etching device outlet nozzle **1108**, and the stage **1114** is rotated and moved in the X direction to position discrete portions of the location on the device **10** where the abnormality is formed and is to be removed under the outlet **1108** of one or more inkjet dispensers **1104**. The outlet nozzle **1008** facing surface of the stage **1114** is located more than the thickness of an optical device **10** from the drop dispensing opening **1010** of the outlet nozzle **1008** exit of the inkjet nozzle, leaving a distance between the nozzle exit and the surface of the encapsulation layer **12** of the optical device **10** on the order of 2 to 5 mm.

[0093] To correct the abnormality in thickness **91** on the outer surface of the encapsulation layer **12** by removing the projection without leaving a significant depression in the underlying encapsulation layer **12**, droplets **1106** of a wet etching or reactive chemistry are dropped onto the projection **91** from one or more outlets **1108** of an ink jet apparatus **1104**. Examples of possible encapsulation layer **12** layer materials and their appropriately paired etchants include the following pairs; SiO2 material and DHF etchant, Si3N4 material and HF or H3PO4 as etchant, TiO2 material and SC1 etchant, a Carbon based material and an organic solvent or a photoresist remover etchant, and an aSI (amorphous silicon) material using KOH etchant. Etching of the 2D wedge **11** abnormality **91** can be done in a film layer and can be performed in a variety of different ways.

[0094] Here, imaging cameras **1130**, **1132** of the inkjet apparatus **1100** are provided and used to locate the abnormality **91** on the encapsulation layer **12** to allow the inkjet apparatus **1100** to locate it directly below the drop dispensing outlet **1110**, so that droplets of etchant which are released land on the abnormality **91**, and not on the surrounding encapsulation layer **12**, as well as used, in conjunction with a controller (not shown) to determine the height of the abnormality and the relative heights of different portions thereof. As the abnormality **91** is etched away by the application of the droplets **1106** of etchant, the profile of the abnormality **91**, and its location, are monitored using the cameras **1130**, **1132**, to allow the stage **1114** to properly position the abnormality **91** under the drop dispensing outlet **1110** to ensure the droplets **1106** land on the abnormality **91** and the portions thereof extending the furthest above the otherwise flat uniform surface **93** of the encapsulation layer **12**, and not on the adjacent portions of the encapsulation layer **12**. Once the abnormality **91** is removed to the otherwise uniform surface **93** of the encapsulation layer as shown in FIG. **9**B, etching is terminated such as rinsing the surface of the encapsulation layer **12** and the exposed portions of the optical layer **19** with a quench chemistry dispensed through the inkjet dispenser **1124** and drop dispensing opening **1110**, with a neutral liquid such as deionized water dispensed through the rinse nozzle **1126**, or with a quench chemistry followed by a neutral liquid wash using, for example, deionized water. Then the device is removed from the stage and mounted in a cleaning and drying station **1128** for washing and drying thereof.

[0095] FIG. **10** is a flowchart providing a sequence of acts used to remove an abnormality **91** extending above the surface **93** of a film layer, such as an encapsulation layer **12**. Initially, at Act **1001**, the device **10**, with the abnormality thereon, on is located on the stage **1114** of the inkjet etching apparatus **1100**. Then, in Act **1003**, the location of the abnormality on the encapsulation layer is established using cameras **1130**, **1132**, and the stage **1114** is moved to position the abnormality below a drop dispensing outlet **1110** of an inkjet dispenser **1104** in Act **1003**. Then, similarly to the process for creating a 2D wedge as described in FIG. **2**, at Act **1005**, droplets of etchant are dispensed onto only the surface of the projection. The droplets are released utilizing the same four strategies as described in FIG. **2** as well as one new additional strategy in Act **1019**. These strategies include the following; removal of the abnormality **91** by quenching variation as described in Acts **1011-1041**, removal of the abnormality **91** by droplet density variation as described in Acts **1013-1043**, removal of the abnormality **91** by concentration variation as described in Acts **1015-1045**, and removal of the abnormality **91** by droplet size variation as described in Acts **1017-1047**. These etching procedures follow the same pattern for creating more or less etching to the desired resulting architecture. In the case of creating a 2D wedge, the wedge may be etched into an already flat surface of the encapsulation layer **12**, while in the case of abnormality correction, removing the abnormality **91** to yield a flat uniform surface **93** of the encapsulation layer **12** may be the desired result. Thus, here, droplets **1106** of etchant are sequentially deposited on the portions of the abnormality **91** extending furthest from the underlying desired flat, uniform, surface **93** are sequentially etched, and those locations will change as the abnormality is being removed. In Act **1019**, etchant droplets of uniform size, density, and concentration are released at the most protruding point of the abnormality **91** above the desired flat uniform surface **93** of the encapsulation layer **12**, which may or may not be the center of the abnormality. As etching continues, the cameras **1130** and **1132** locate where the most

protruding, above the desired flat uniform surface **93** of the encapsulation layer **12**, location(s) of the abnormality is, and the stage **1114** of the inkjet etching device **1100** is moved to locate the most protruding location of the abnormality **91** underneath the drop dispensing outlet **1110** of the inkjet dispenser **1104**. Droplets are then dispensed again, and the sequence of locating of the most protruding portions of the abnormality, and dispensing droplets **1106** to that location, is repeated until the abnormality **91** is coplanar with the desired flat, uniform surface **93** of the encapsulation layer **12**. When this planarity is reached, etching is terminated in Act **1029**, such as by supplying a quenching chemistry on the abnormality **91** and adjacent portions of the encapsulation layer, supplying a rinsing liquid such as deionized water to wash away the etchant, or a combination thereof. Then, in Act **1039**, the device is moved to a cleaner and cleaned and dried in Act **1049**.

[0096] Referring to FIGS. **12**B and **12**C, a schematic side view of an optical device **10** with a uniform encapsulation layer **12** thereon, (FIG. **12**B) and a 1D wedge **121** formed in the encapsulation layer **12** (FIG. **12**C) is shown. The optical device **10** in FIG. **12**B includes an encapsulation layer **12**, in which a 1D wedge **121** here is created using an inkjet wet etching device **1100** to dispense an etchant to selectively, locally, remove material from the encapsulation layer to locally form the smooth and angled surface of the encapsulation layer **12** of FIG. **12**C to form the underlying 1D wedge **121**. Here, in contrast to the 2D wedge structures previously described here, where the depth of the surface feature being etched into the surface of a layer in the z direction changes in both the X and the Y directions, here, the depth of the surface feature being etched into the surface of a layer in the z direction changes in only one of the x and y directions, resulting in a ramp feature having a planar outer surface, i.e., a simple 1D wedge. As described herein, the depth of the feature is changing in only the x direction, and is constant across any Y direction thereof, the depth of the feature in adjacent Y location directions adjacent to one another in the X direction changing. This is accomplished by performing the same material removal across each Y-direction section of the feature, and increasing or decreasing the material removal at adjacent Y direction locations of the feature. As discussed herein, this can be accomplished in several ways, including applying a blanket material removal agent, i.e., an etchant, over the entire area of a surface where a wedge is to be formed, and selectively quenching the reaction across the Y direction of the surface, starting at the X_o end of the feature and ending at the X_e end of the region, wherein a plurality of n regions extend in the Y direction across the region where the feature to be formed. Here, the width of the individual regions Y_1-Y_n in the X-direction are selected, for example, to enable discrete regions extending across the area where the 1D wedge **121** is to be formed in the Y direction having the same quench timing, or exposure of the underlying material to the etchant time period, and each adjacent region having a different quench timing, or exposure of the underlying material to the etchant time period. In FIG. **12**D, region Y_o has the fasted quench timing, in other words is quenched before any other region is quenched, the next region Y_1 has the next fasted quench timing, and each adjacent region Y_2 to Y_n has a correspondingly longer quench timing. As a result, the depth of region Y_o in the Z direction is less than the depth of region Y_1 in the Z direction, the depth of region Y_1 in the Z direction is less than the depth of region Y_2 in the Z direction, the depth of region Y_2 in the Z direction is less than the depth of each subsequent region Y_3 to Y_n in the Z direction, and ultimately the depth of region Y_{n-1} in the Z direction is less than the depth of region Y_n in the Z direction. Thus a feature having a sloped outer surface extending inwardly into the surface of the encapsulation layer **12** is formed. The smaller the width of each of the individual regions Y_1-Y_n in the X direction, the smoother the transition from the depth of region Y_1 to the depth of region Y_n, such that as the width of each Y region approaches 0 in the X-direction, the more planar the outer surface of the 1D wedge **121** becomes.

[0097] In another aspect, the 1D wedge **121** can be formed by changing the density of the droplets of etchant dispensed in the X direction, but maintaining the same density of droplets in the Y direction at each X location. As the etchant is consumed by reaction with the underlying material into which the wedge is being formed, the etch rate will fall and may reach 0 in regions were fewer droplets are dispensed, while areas where the wedge feature is etched deeper into the layer, i.e., where a greater number of droplets than adjacent, in the X direction Y regions, continue to etch inwardly of the layer, and a 1D wedge **121** as shown in FIGS. **12**C and **12**D can be formed. Again, the droplets **1106** can be dispensed in regions Y_o-Y_n in the X direction, where the number of droplets in each individual Y region is the same, but the number of droplets is different in Y regions there-adjacent in the X direction. Thus, a wedge feature having the properties of FIGS. **12**C and D is formed.

[0098] In another aspect, the 1D wedge **121** is formed by changing the etchant concentration in the droplets dispensed in adjacent Y regions in the X direction, but again maintaining the etchant concentration of the droplets **1106** in each of the regions Y_o-Y_n constant in Y direction. Similarly, the size of the etchant droplets can be changed over the area of the to be formed wedge **121**, where the etchant concentration in the droplets is the same. Hence, by depositing the smallest droplets in the entirety of region Y_o, and sequentially increasing the droplet size in each subsequent region Y_o-Y_n, the wedge feature of FIGS. **12**C and D can be formed.

[0099] FIG. **14** is a flowchart showing a series of activities for creating a 1D wedge **121** in an encapsulation layer **12** of an optical device **10** according to the sequence of processes described with respect to FIG. **12**. Initially, an optical layer **19** is prepared. However, the encapsulation layer **12** may need to have a varied thickness to create a desired effect for the optical device **10**, thus the forming of a 1D wedge **121** can be performed. Herein, the process sequence for forming of the 1D wedge in the encapsulation layer **12**, is described.

[0100] At Act **1301** the optical device **10** is placed on the stage **1114** of the inkjet wet etching device **1100**, and in Act **1303**, positioned by the stage **1114** within the inkjet wet etching device **1100**, by movement in the X and Θ directions of FIG. **11**, to position the desired locale on the encapsulation layer **12** where the 1D wedge is to be formed below drop dispensing opening **1110** of an outlet nozzle **1108** of an ink jet dispenser **1104**. At Act **1305** an etchant capable of reacting with (etching) the material of the encapsulation layer **12** is released from the drop dispensing opening as droplets **1106**. Preferably, this etchant has an etch rate of the material of the optical layer **19** on the order of more than 100 times less than the etch rate for the encapsulation layer **12** when exposed to that same etchant.

[0101] In one aspect, after etchant is released to the outlet nozzle **1108***a* through line **1118***a* to cover the entire area where the wedge profile **11***a* to form the wedge **121** is to be formed, a quenching chemistry is immediately thereafter released to Y_0 region of the wedge profile **11***a* being formed in Act **1311**. The higher subscript number Y regions of the encapsulation layer of the being-formed wedge profile **11***a* sequentially receive the quenching chemistry thereafter by movement of the stage **1114** to position discrete areas of the encapsulation layer **12** under the stream of drops **1106** of the quenching chemistry at a pre-determined time at which the wedge profile **121***a*, at that location, has removed sufficient material to form the desired encapsulation layer **12** thickness of the wedge profile **11***a* thereat in which the amount on material removed is the same in the Y direction and varies in the X direction, to get a planar feature that extends into the layer **12** in the Z direction at a constant rate per length of X direction. Once the entire surface of the wedge profile **11***a* region of the encapsulation layer **12** has been quenched, At Act **1321** the surface is then washed by deionized water, dispensed by rinse nozzle **1126**, to remove etched debris, any remaining etchant, quenching chemical, and any byproduct formed therein. At Act **1331** the optical device **10** with the wedge **11** formed therein is then removed from the stage **1114** and positioned in Act **1341***a* cleaning and drying station **1128** having a spin rinse chuck **1130** to further clean and dry the device.

[0102] In a second aspect, deeper etching is achieved by dispensing sequentially more droplets in adjacent Y regions having increasing subscript numbers in the X direction, but again maintaining the etchant droplet density constant in Y direction of the regions Y_o-Y_n. Hence, by depositing the smallest droplet density in the entirety of region Y_o, and sequentially increasing the droplet density in each subsequent region Y_o-Y_n, the wedge feature of FIGS. **12**C and D can be formed in Act **1313**, by movement of the stage **1114** and consequently the encapsulation layer **12** under the stream of droplets **1106**. Alternatively, where the droplets have a relatively high viscosity so as not to significantly move from their location of being dropped on the encapsulation, more droplets **1106** can be dropped in deeper locations of the wedge profile **121***a* to be formed than at shallower regions thereof in a single pass of the wedge profile **121***a* forming region of the encapsulation layer **12** under the drop dispensing outlet **1010**, so that a thicker layer of etchant is present over the deeper locations of the wedge profile **11***a* to be formed than at shallower regions thereof. In Act **1323** the surface of the encapsulation layer **12** including the 1D wedge **121** is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed from the support **1114** in act **1333** and positioned in a cleaning and drying station **1128** in Act **1343** to be further cleaned and dried.

[0103] In the third aspect, in Act **1305** the etchant is released in droplets **1106** of different etchant concentration at different locations of the wedge profile **121***a* being formed. Droplets are dispensed in adjacent Y regions in the X direction, but again maintaining the etchant concentration of the droplets constant in Y direction of the regions Y_o-Y_n. Hence, by depositing the smallest droplet concentration in the entirety of region Y_o, and sequentially increasing the droplet concentration in each subsequent region Y_o-Y_n, the wedge feature of FIGS. **12**C and D can be formed in Act **1315**. The surface of the encapsulation layer **12** including the 1D wedge **121** is then washed by deionized water in Act **1325**, dispensed by rinse nozzle **1126**, to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. From here, the optical device **10** will be removed in Act **1335** from the support **1114** and positioned in a cleaning and drying station **1128** in Act **1345** to be further cleaned and dried.

[0104] In a fourth aspect, the etchant released in Act **1305** deeper etching is achieved by dispensing larger sized droplets in adjacent Y regions in the X direction, but again maintaining the etchant droplet size constant in Y direction of the regions Y_o-Y_n in Act **1317**. Hence, by depositing the smallest droplet size in the entirety of region Y_o, and sequentially increasing the droplet size in each subsequent region Y_o-Y_n, the wedge feature of FIGS. **12**C and D can be formed. In act **1327** the surface of the encapsulation layer **12** with the 1D wedge **121** formed therein is then washed by deionized water, dispensed by wash nozzle **1126** to remove etched debris, etchant, quenching chemical, and any byproduct formed therein. In Act **1337**, the optical device **10** will be removed from the support **1114** and positioned in a cleaning and drying station **1128** in Act **1347** for further cleaning and drying thereof.

[0105] In at least some embodiments hereof, surfactants are used to alter etching capabilities of the previously mentioned etching strategies. Surfactants are used to change the surface energy of the droplets. Where the surface energy of the droplet is less than the surface energy of the surface it is received on, the droplet spreads out. The higher the droplet surface energy compared to the surface energy on the surface on which it is dropped, the less the droplet spreads out. Thus, herein, one can change the local intermixing of the droplets adjacent to one another on the to-be-etched or being etched surface by selectively adding surfactant thereto, and thereby allow the droplets dispensed adjacent to each other to blend together, or stay substantially isolated from one another.

[0106] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method of forming a three dimensional feature inwardly of a surface of a material, comprising:

providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material having a reactant therein capable of reacting with, and thereby removing, portions of the material layer with which the droplets come into contact;

providing a support configured support the material thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material; and

positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the surface of the material in a desired area thereof, to remove at least a portion of the material in the desired area and thereby form a three dimensional recess inwardly of the surface of the material.

2. The method of claim **1**, further comprising dispensing different amounts of droplets of the liquid material to different portions of the desired area.

3. The method of claim **2**, wherein, across the span of the desired area, the number of droplets dispensed is greater in regions where the 3 dimensional feature being formed is deeper.

4. The method of claim **1**, wherein the droplets of liquid material dispensed from the droplet dispenser have a uniform concentration of the reactant;

the droplets of liquid are dispensed over the entire desired area, and

a quenching chemistry is applied to the desired area over a span of time, wherein portions of the desired area in which a greater amount of material is to be removed receive etchant at a later time than portions of the desired area in which a lesser amount of material s to be removed.

5. The method of claim **4**, wherein the liquid droplets have the same concentration of reactant.

6. The method of claim **1**, further comprising providing liquid droplets having different concentrations of the reactant therein to different discrete portions of the desired area.

7. The method of claim **6**, wherein droplets having a greater concentration of the reactant therein are dispensed to discrete portions of the area where the three dimensional feature being formed is to be deeper, and droplets having a lower concentration of the reactant therein are dispensed to discrete portions of the area where the three dimension feature being formed is to be shallower than the deeper portions thereof.

8. The method of claim **1**, further comprising providing liquid droplets having different volumes to different discrete portions of the desired area.

9. The method of claim **8**, wherein the droplets having different volumes have the same concentration of the reactant therein.

10. The method of claim **8**, wherein the droplets having a larger volume are dispensed to discrete portions of the area where the three dimensional feature being formed is to be deeper, and droplets having a lower volume are dispensed to discrete portions of the area where the three dimension feature being formed is to be shallower than the deeper portions thereof.

11. The method of claim **1**, wherein the surface of the material is an abnormal feature, further comprising dispensing liquid droplets to form a three dimensional feature inwardly of the surface of the abnormal feature.

12. The method of claim **1**, wherein the material is disposed over an underlying second material, and the first material is removed in the area to expose the underlying surface of the underlying second material.

13. A material layer having a three dimensional feature therein, fabricated by:

providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material having a reactant therein capable of reacting with, and thereby removing, portions of the material layer with which the droplets come into contact;

providing a support configured support the material thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material;

positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the surface of the material in a desired area thereof, to remove at least a portion of the material in the desired area and thereby form a three dimensional recess inwardly of the surface of the material.

14. The material layer of claim **13**, further comprising dispensing different amounts of droplets of the liquid material to different portions of the desired area.

15. The material layer of claim **13**, wherein the droplets of liquid material dispensed from the droplet dispenser have a uniform concentration of the reactant;

the droplets of liquid are dispensed over the entire desired area, and

a quenching chemistry is applied to the desired area over a span of time, wherein portions of the desired area in which a greater amount of material is to be removed receive etchant at a later time than portions of the desired area in which a lesser amount of material s to be removed.

16. The material layer of claim **13** further comprising providing liquid droplets having different concentrations of the reactant therein to different discrete portions of the desired area.

17. The material layer of claim **13**, further comprising providing liquid droplets having different volumes to different discrete portions of the desired area.

18. A method of forming a patterned photoresist on a material layer, comprising;

providing a droplet dispenser including an outlet configured to dispense discrete droplets of a liquid material therefrom;

providing a support configured support the material layer thereon, the support, and the droplet dispenser, movable with respect to one another, such that the outlet of the droplet dispenser is positionable over different discrete areas of the surface of the material;

providing a first liquid, dispensable from the droplet dispenser in droplet form, comprising a photoresist polymer;

providing a second liquid, comprising a sensitizer which, when intermixed with the polymer, changes a reactivity of the polymer to electromagnetic energy;

positioning the surface of the material under the droplet dispenser, and dispensing droplets to discrete portions of the first liquid to the entire surface of the material layer, and dispensing droplets of the second liquid only on a desired, discrete area of the material layer to intermingle the first liquid and the second liquid in the desired, discrete area of the material layer.

19. The method of claim **18**, wherein within the discrete area, different amounts of the first liquid are dispensed to different portions of the discrete area.

20. The method of claim **19**, wherein multiple sublayers of the first liquid are sequentially coated onto the material layer, the first sublayer on the material layer and the subsequent sublayers formed one over the other, and, the portion of the discrete area receiving the second liquid is increased from the first sublayer to the final sublayer being formed.

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