US009815697B2

(12) **United States Patent**
Lemaire et al.

(10) **Patent No.: US 9,815,697 B2**
(45) **Date of Patent: Nov. 14, 2017**

(54) **APPARATUS FOR GROWING CARBON NANOTUBE FORESTS, AND GENERATING NANOTUBE STRUCTURES THEREFROM, AND METHOD**

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(73) Assignee: **GrandNano, LLC**, Burnsville, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 233 days.

(21) Appl. No.: **14/501,046**

(22) Filed: **Sep. 30, 2014**

(65) **Prior Publication Data**

US 2015/0020954 A1 Jan. 22, 2015

Related U.S. Application Data

(62) Division of application No. 14/049,180, filed on Oct. 8, 2013, now Pat. No. 8,845,941, which is a division

(Continued)

(51) **Int. Cl.**

B29C 65/00 (2006.01)
C01B 31/02 (2006.01)

(Continued)

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

CPC ***C01B 31/0226*** (2013.01); ***B29C 65/7858*** (2013.01); ***B29C 65/7897*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC C01B 31/0226; B29C 65/7858; B29C 65/7897

See application file for complete search history.

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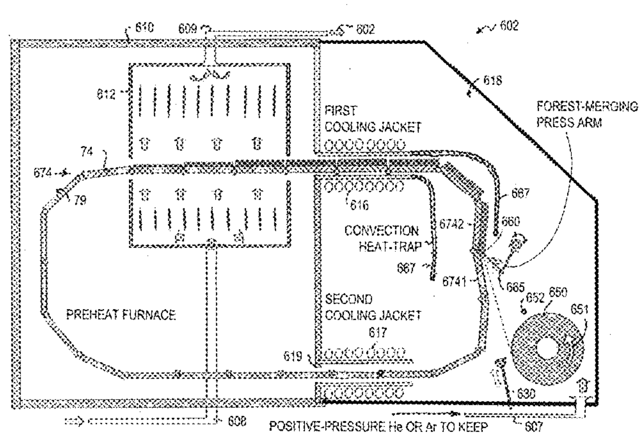
Primary Examiner — Timothy Kennedy

(74) *Attorney, Agent, or Firm* — Charles A. Lemaire; Jonathan M. Rixen; Lemaire Patent Law Firm, P.L.L.C.

(57) **ABSTRACT**

The present invention provides apparatus and methods for growing fullerene nanotube forests, and forming nanotube films, threads and composite structures therefrom. In some embodiments, an interior-flow substrate includes a porous surface and one or more interior passages that provide reactant gas to an interior portion of a densely packed nanotube forest as it is growing. In some embodiments, a continuous-growth furnace is provided that includes an access port for removing nanotube forests without cooling the furnace substantially. In other embodiments, a nanotube film can be pulled from the nanotube forest without removing the forest from the furnace. A nanotube film loom is described. An apparatus for building layers of nanotube films on a continuous web is described.

20 Claims, 47 Drawing Sheets



Related U.S. Application Data

of application No. 13/454,091, filed on Apr. 24, 2012, now Pat. No. 8,551,376, which is a division of application No. 12/794,704, filed on Jun. 4, 2010, now Pat. No. 8,162,643, which is a division of application No. 11/220,455, filed on Sep. 6, 2005, now Pat. No. 7,744,793.

(51) **Int. Cl.**

B82Y 30/00	(2011.01)
B82Y 40/00	(2011.01)
D01F 9/133	(2006.01)
B29C 65/78	(2006.01)
B29K 101/00	(2006.01)

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

CPC ***B82Y 30/00*** (2013.01); ***B82Y 40/00*** (2013.01); ***C01B 31/0213*** (2013.01); ***C01B 31/0233*** (2013.01); ***D01F 9/133*** (2013.01); *B29K 2101/00* (2013.01); *C01B 2202/06* (2013.01); *Y10S 977/842* (2013.01)

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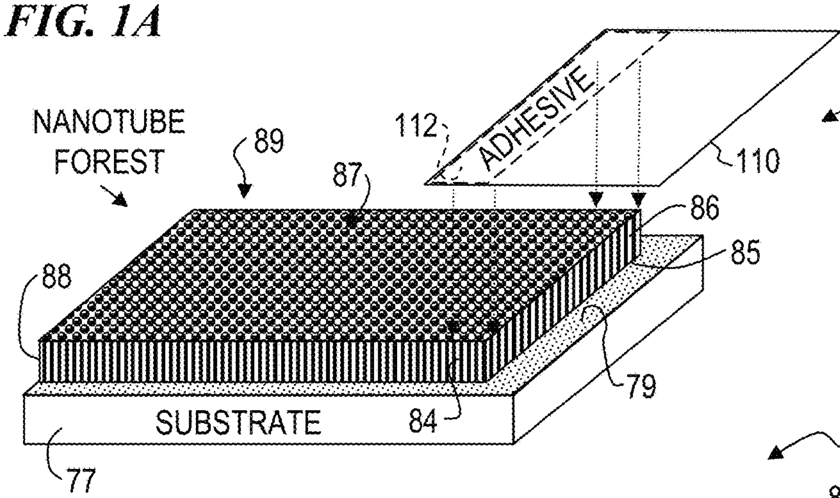
FIG. 1A



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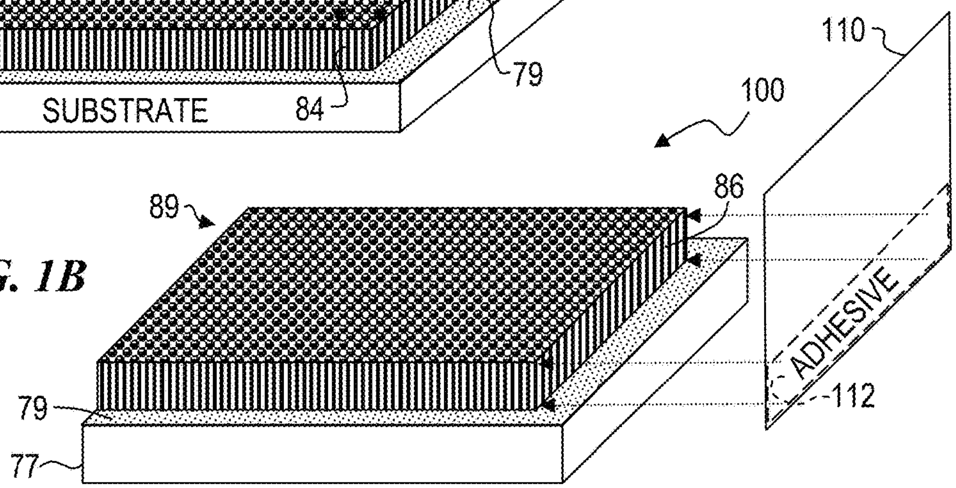

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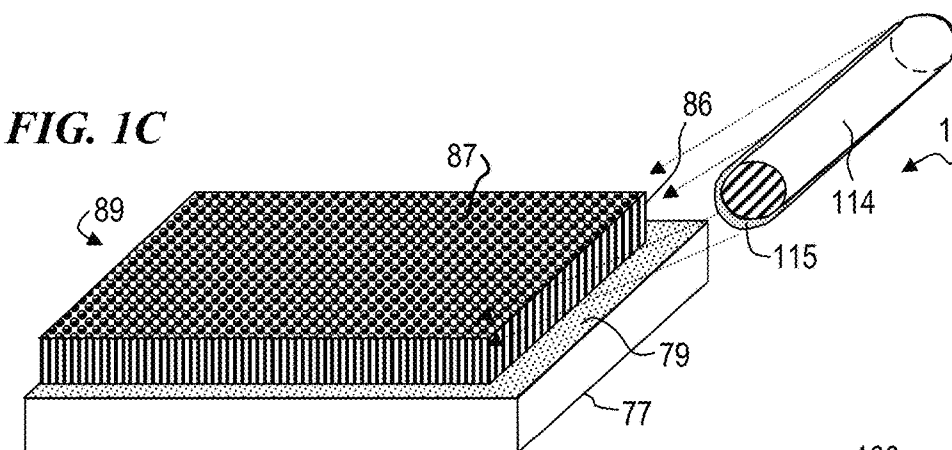

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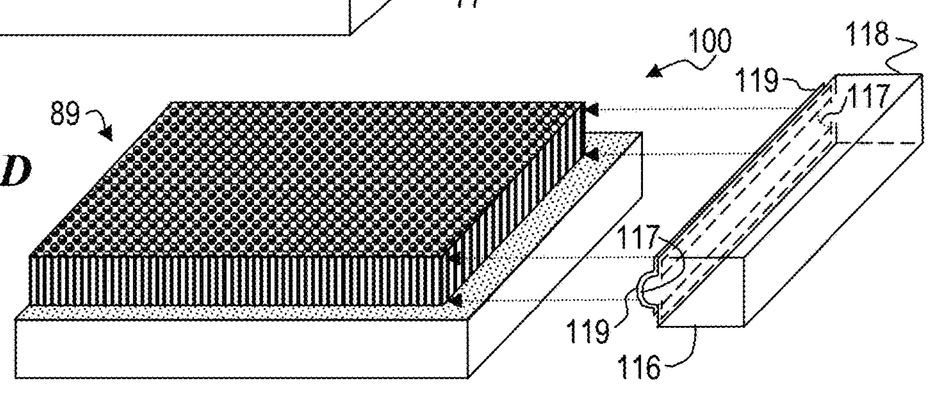


FIG. 1E

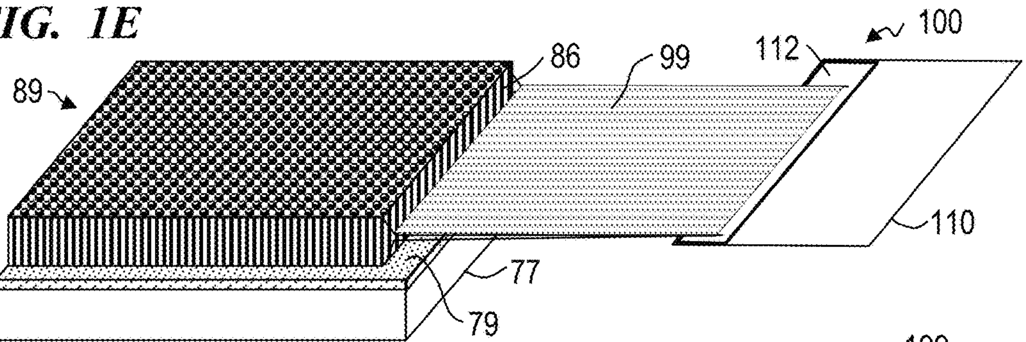


FIG. 1F

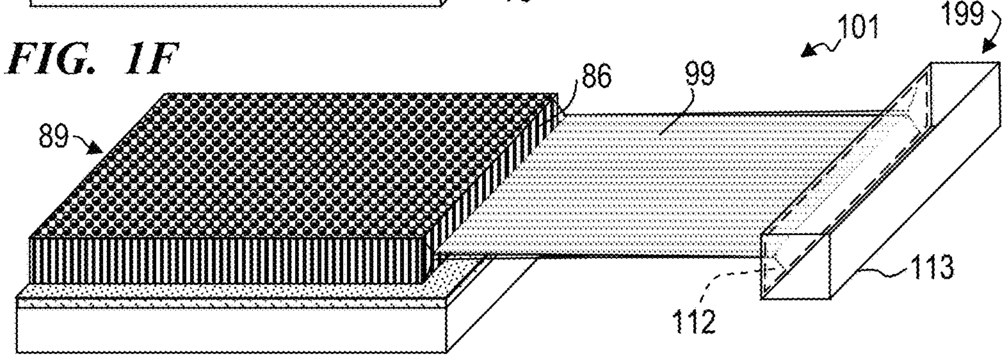
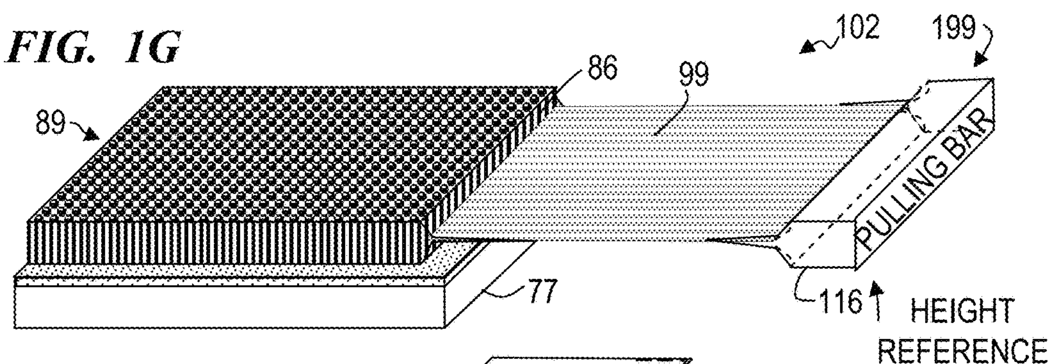


FIG. 1G



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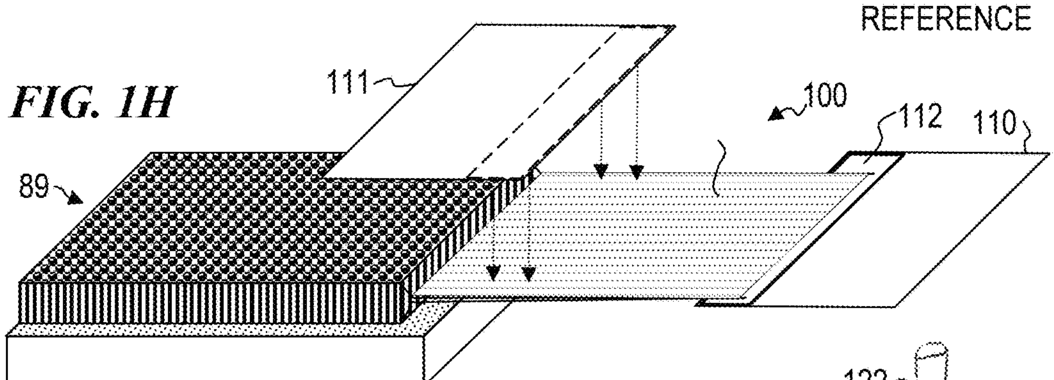

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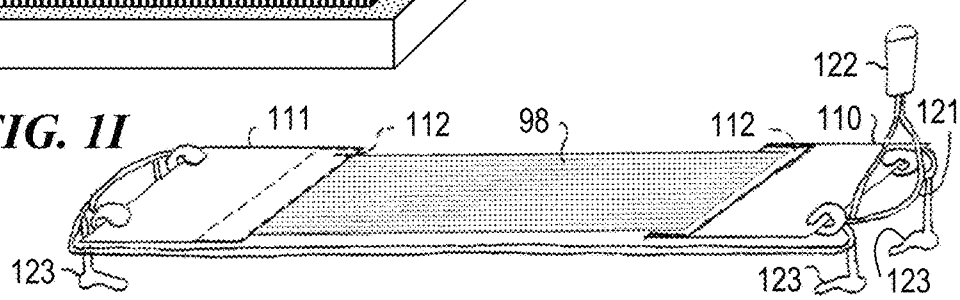

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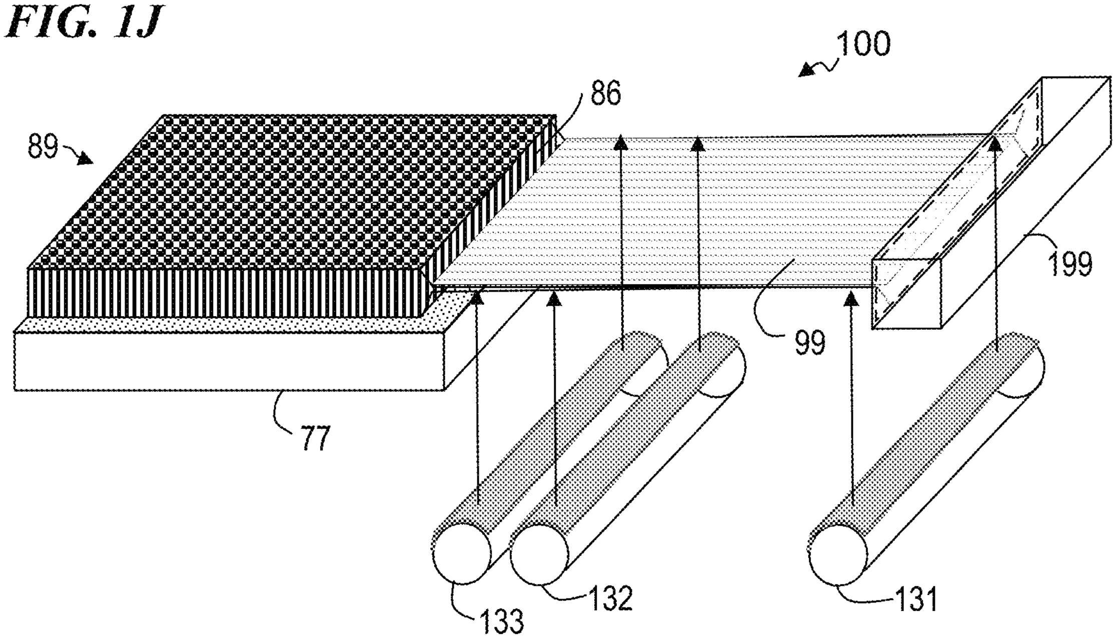
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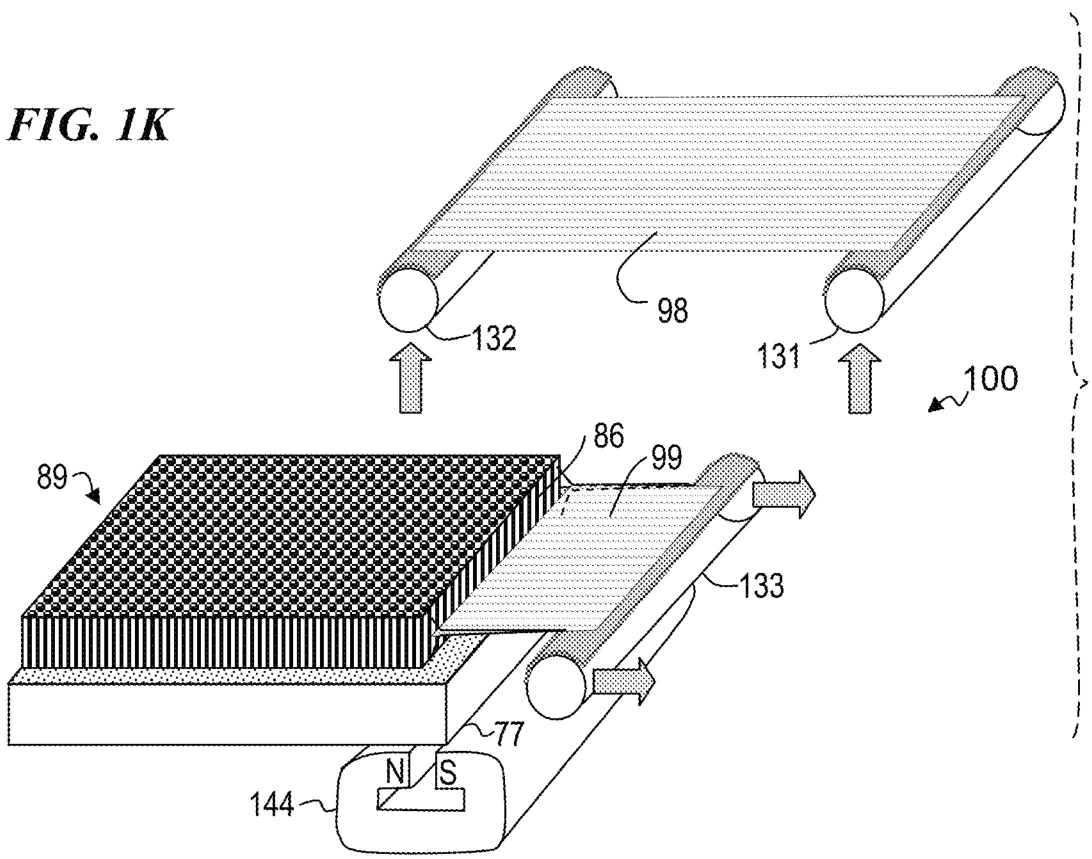
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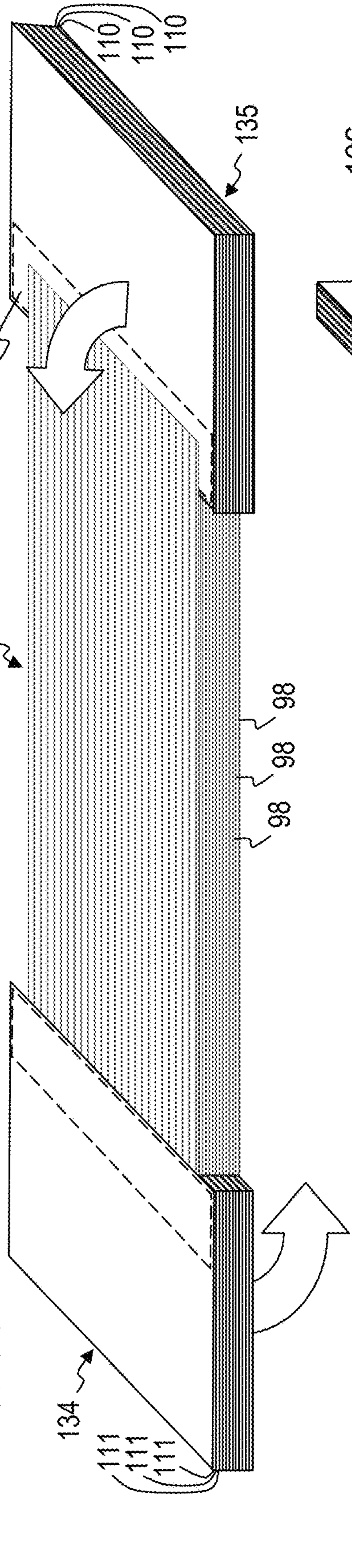
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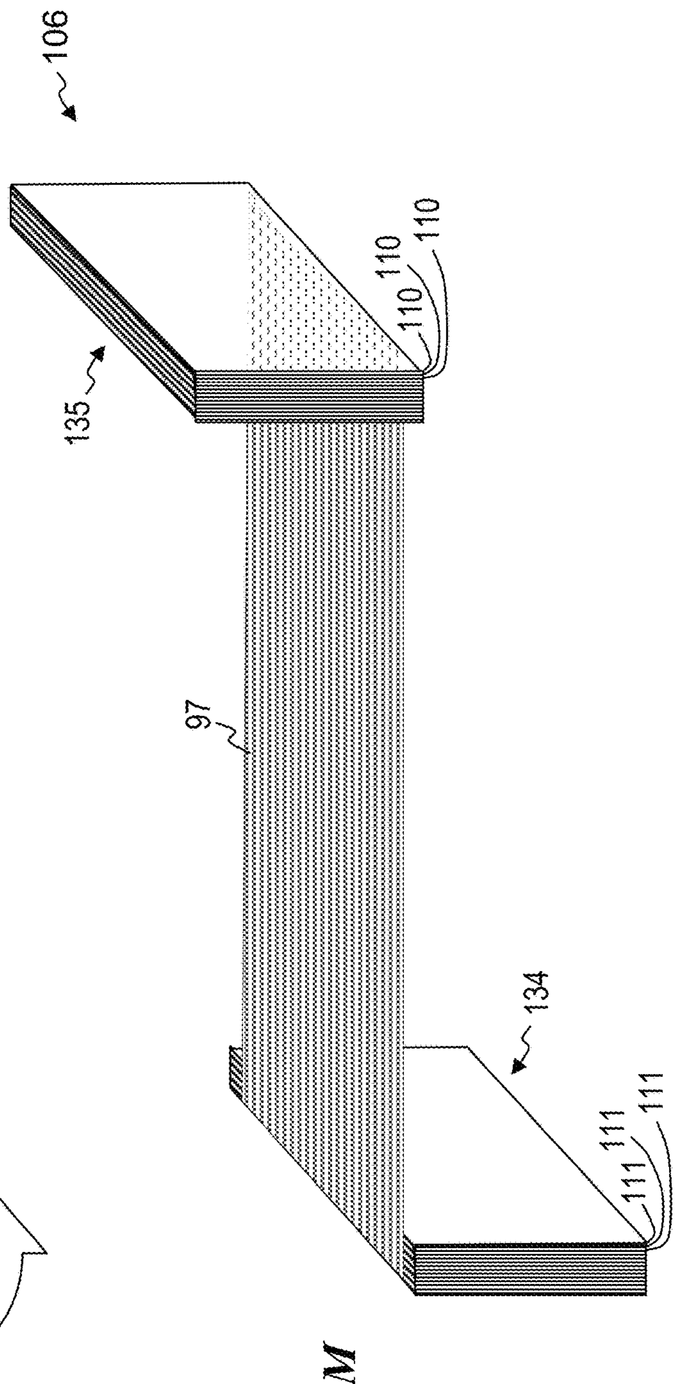
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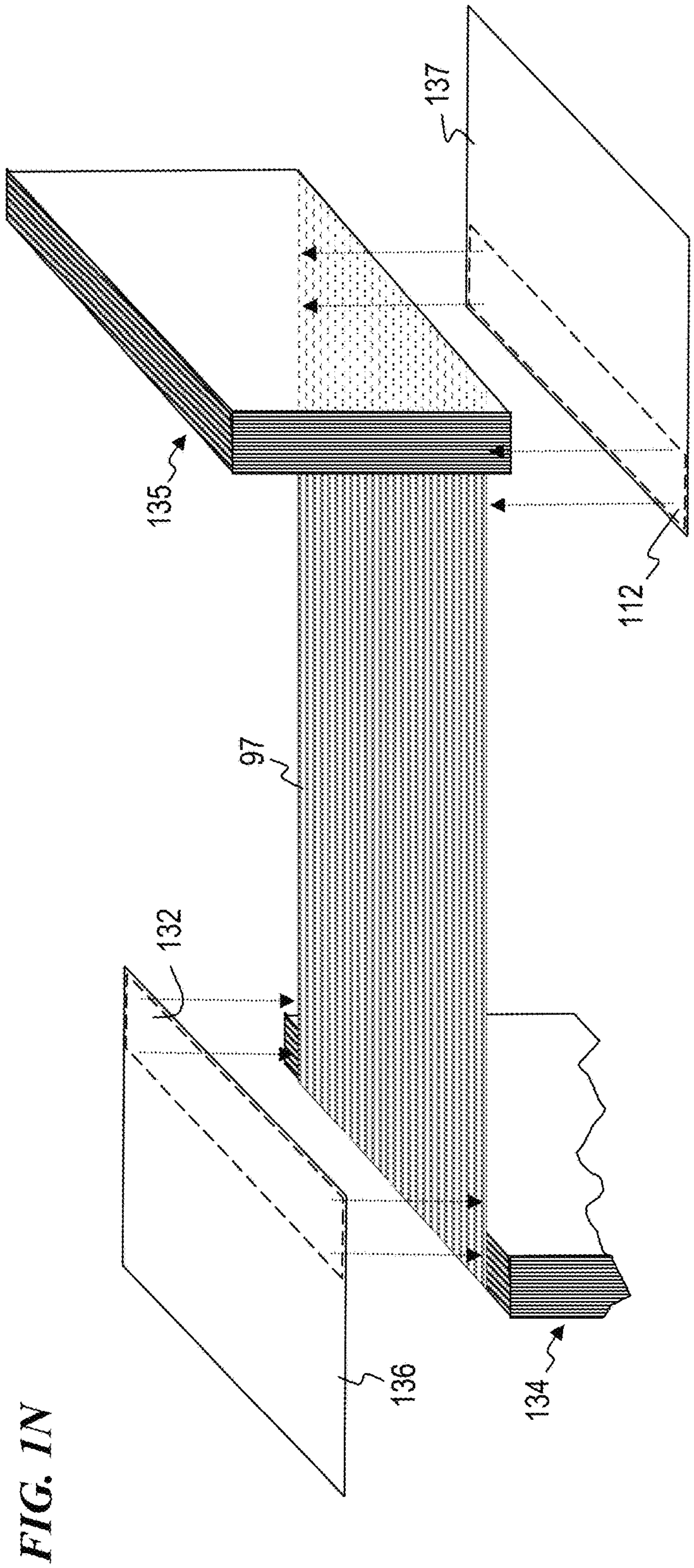

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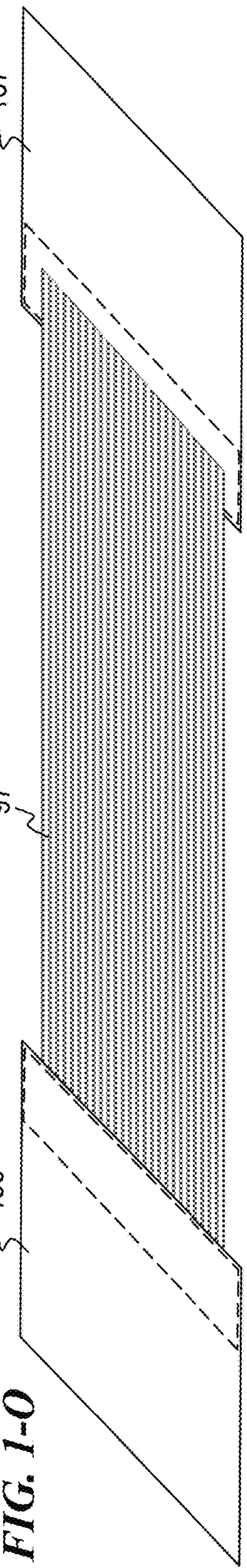

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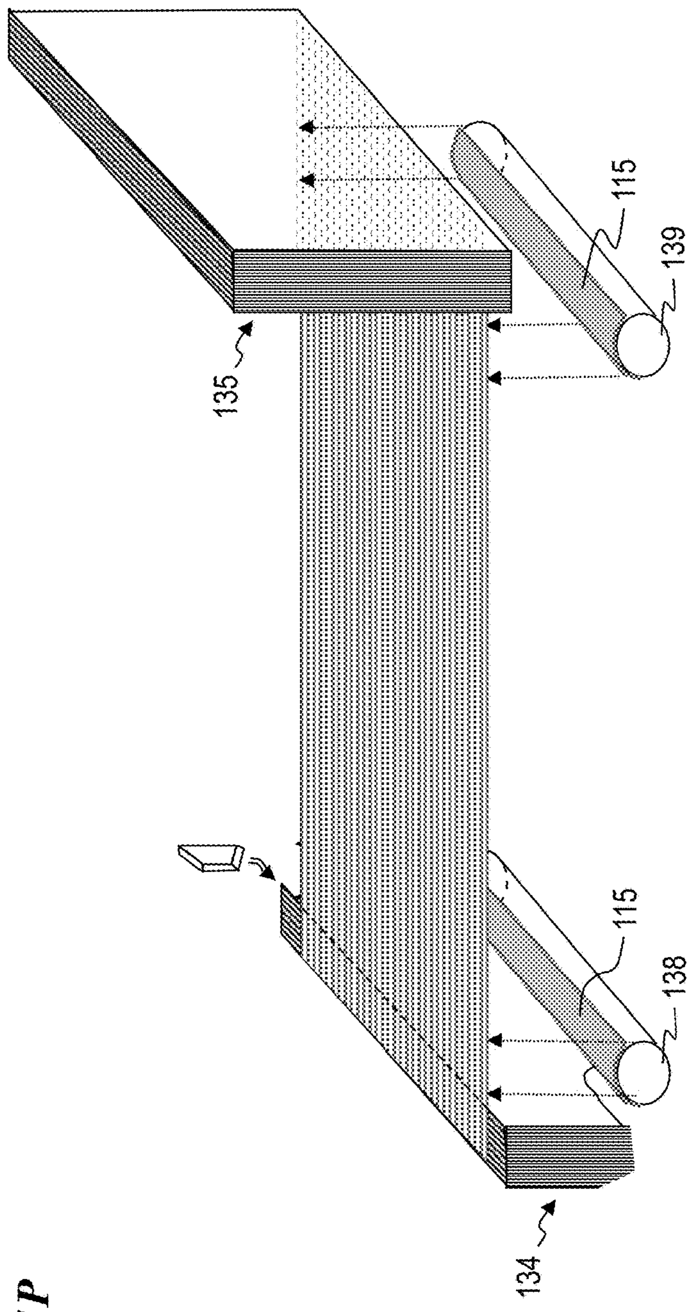

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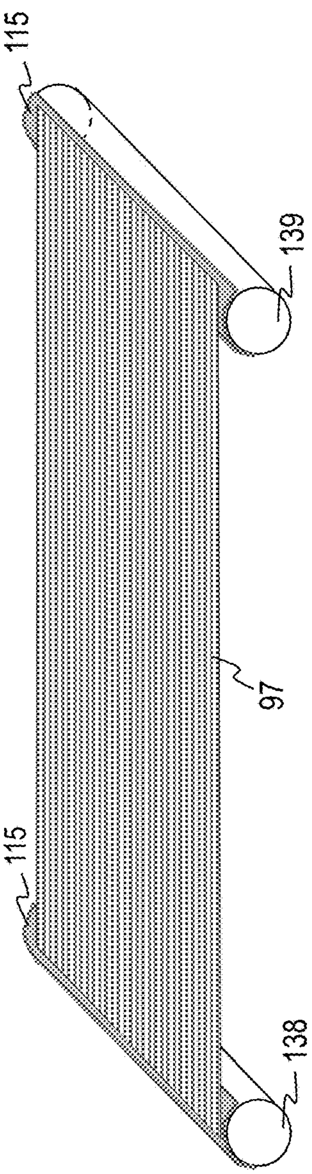
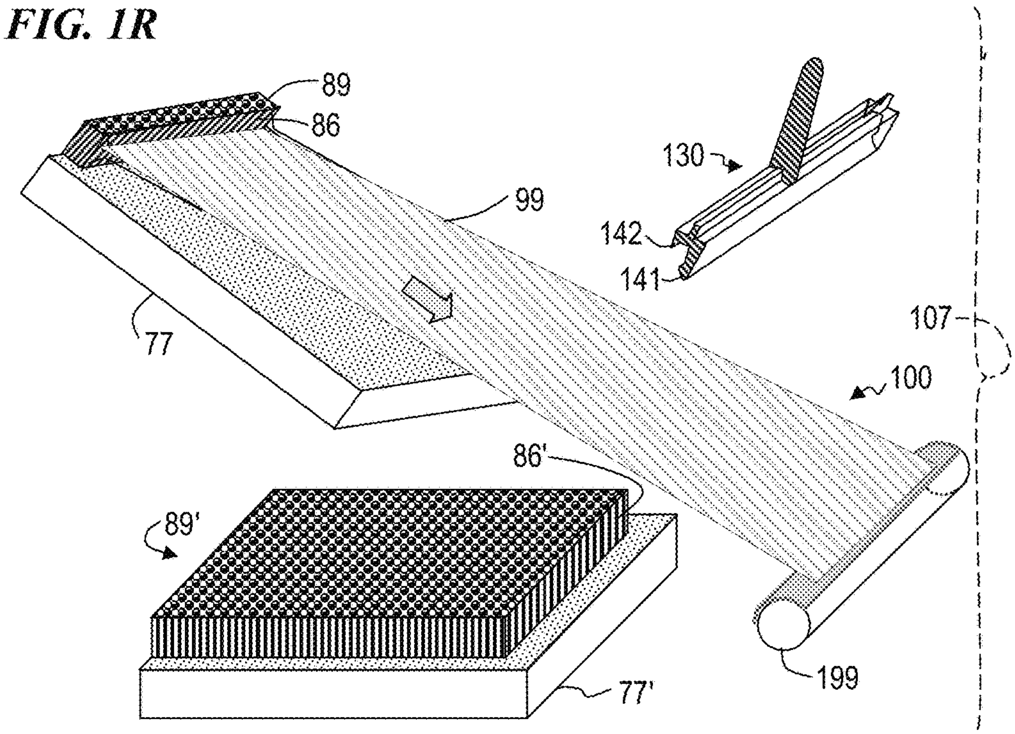


FIG. 1Q

FIG. 1R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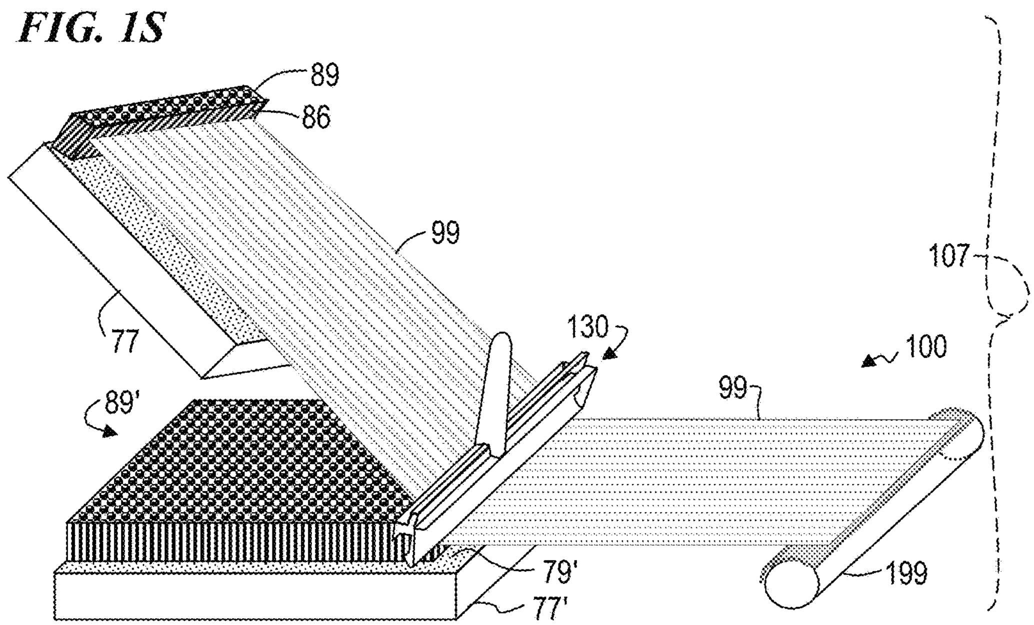
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FIG. 1T

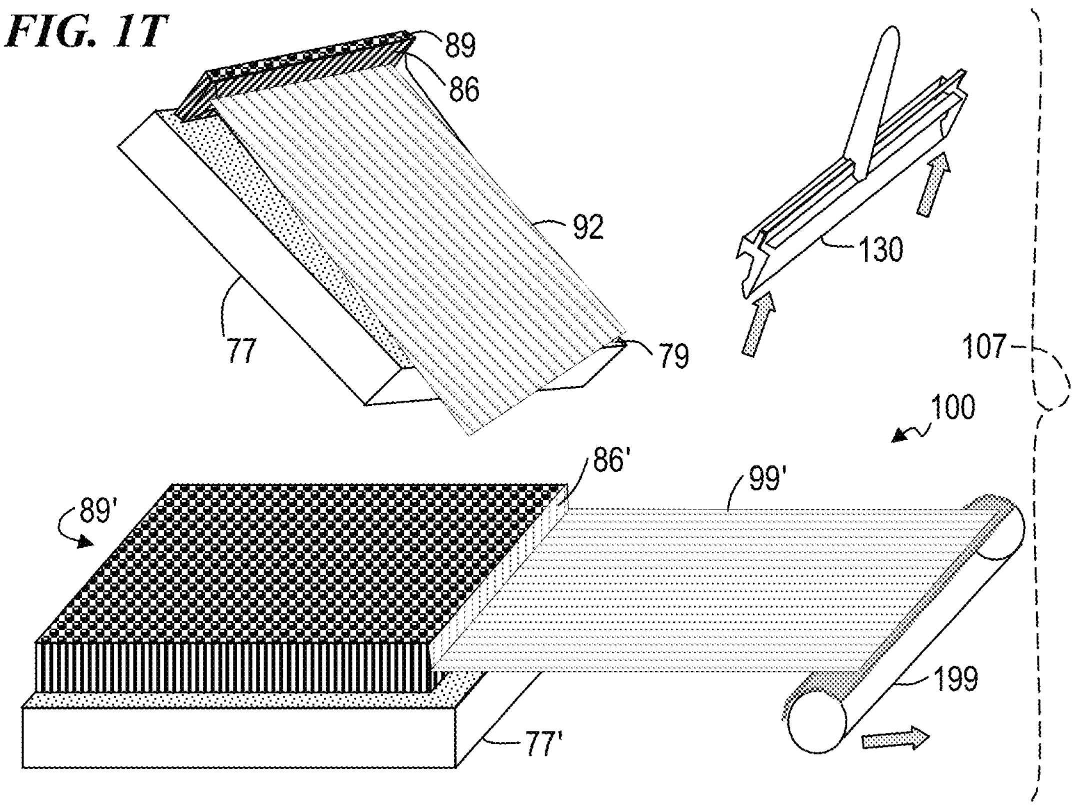
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FIG. 1U

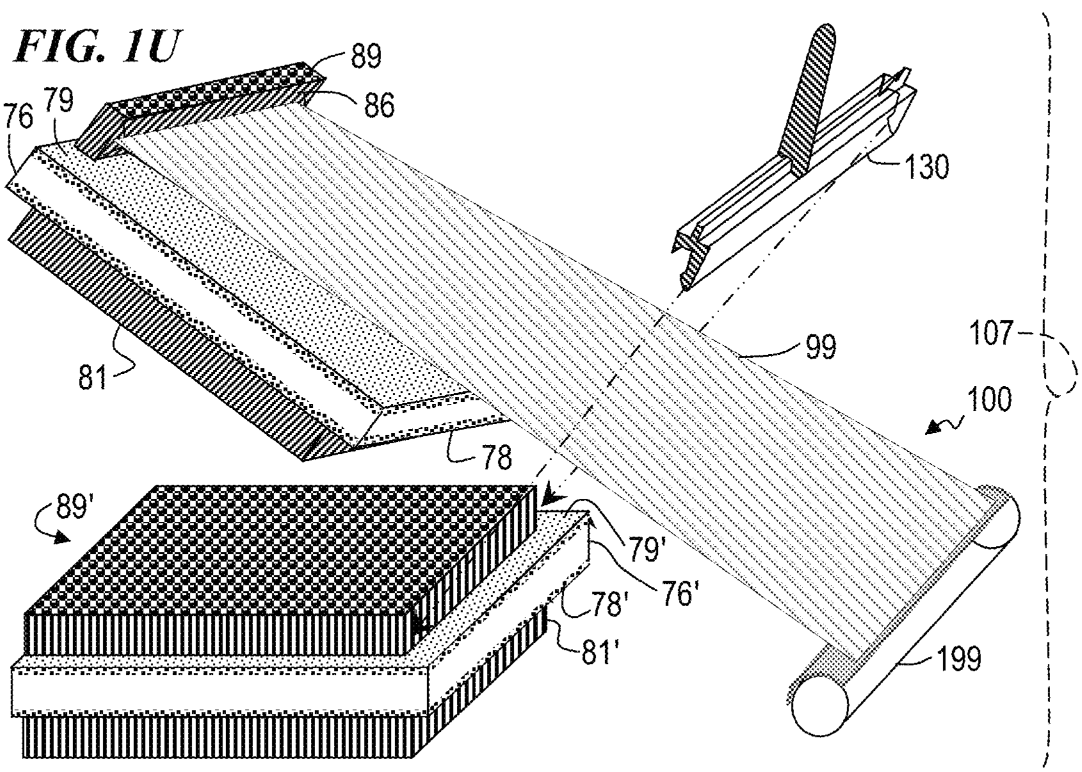
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FIG. 1V

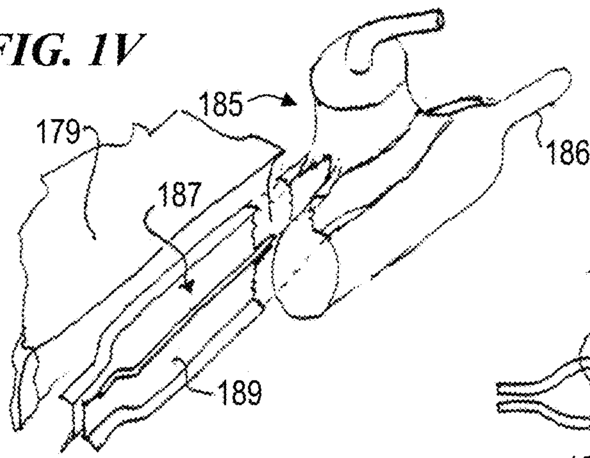


FIG. 1W

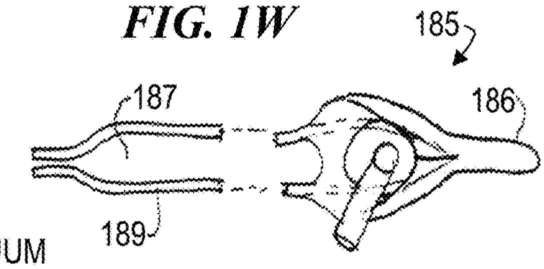
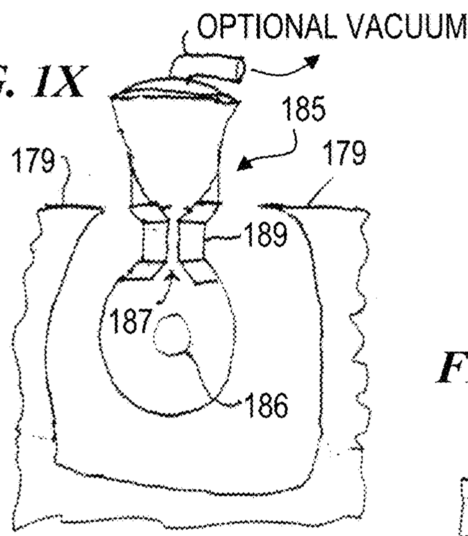


FIG. 1X



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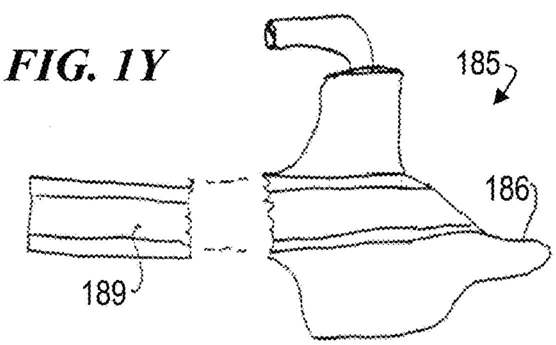

FIG. 1Z

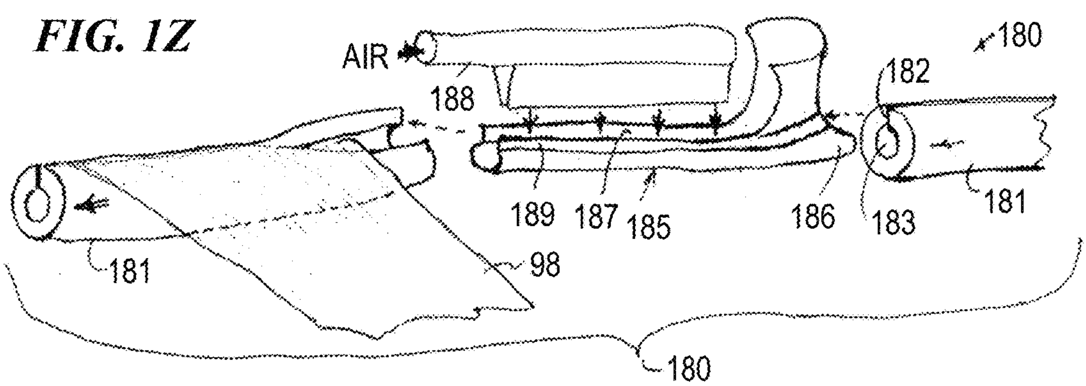

FIG. 2A

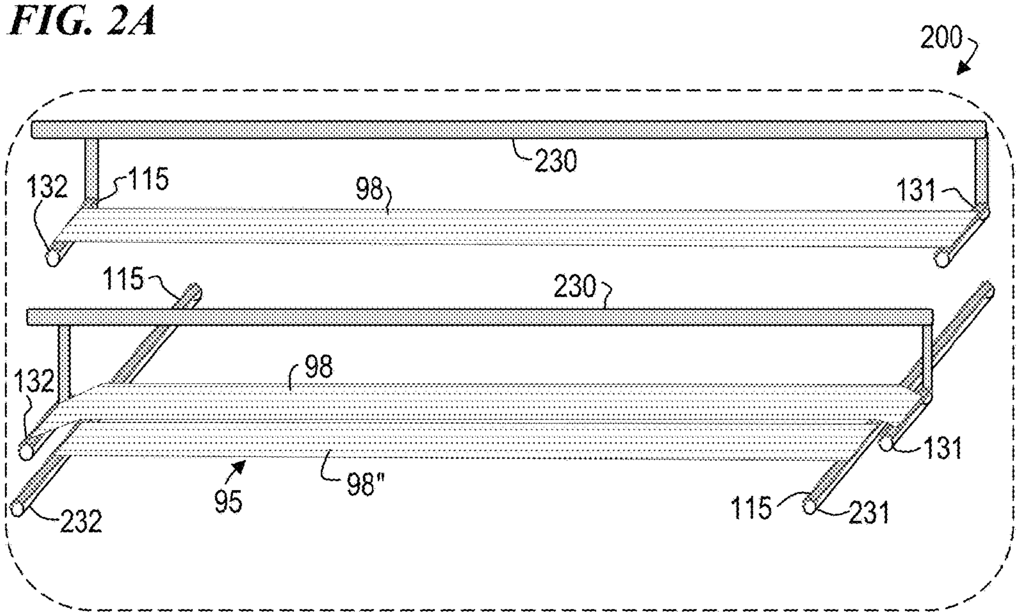
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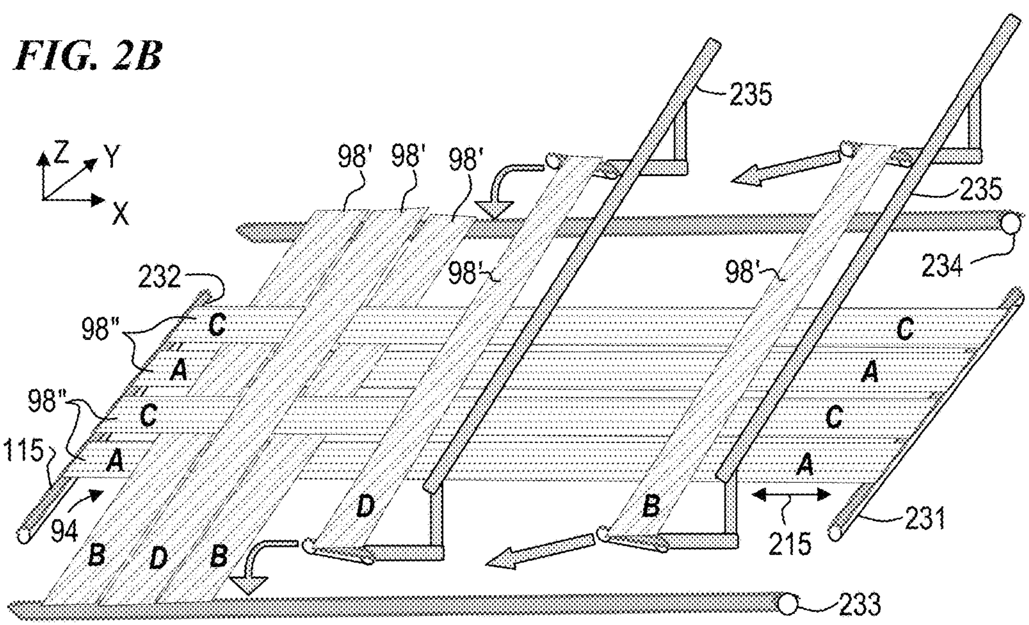
FIG. 2B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98'
98"
C
A
C
A
98"
C
C
115
A
A
94
D
B
215
231
B
D
B
233

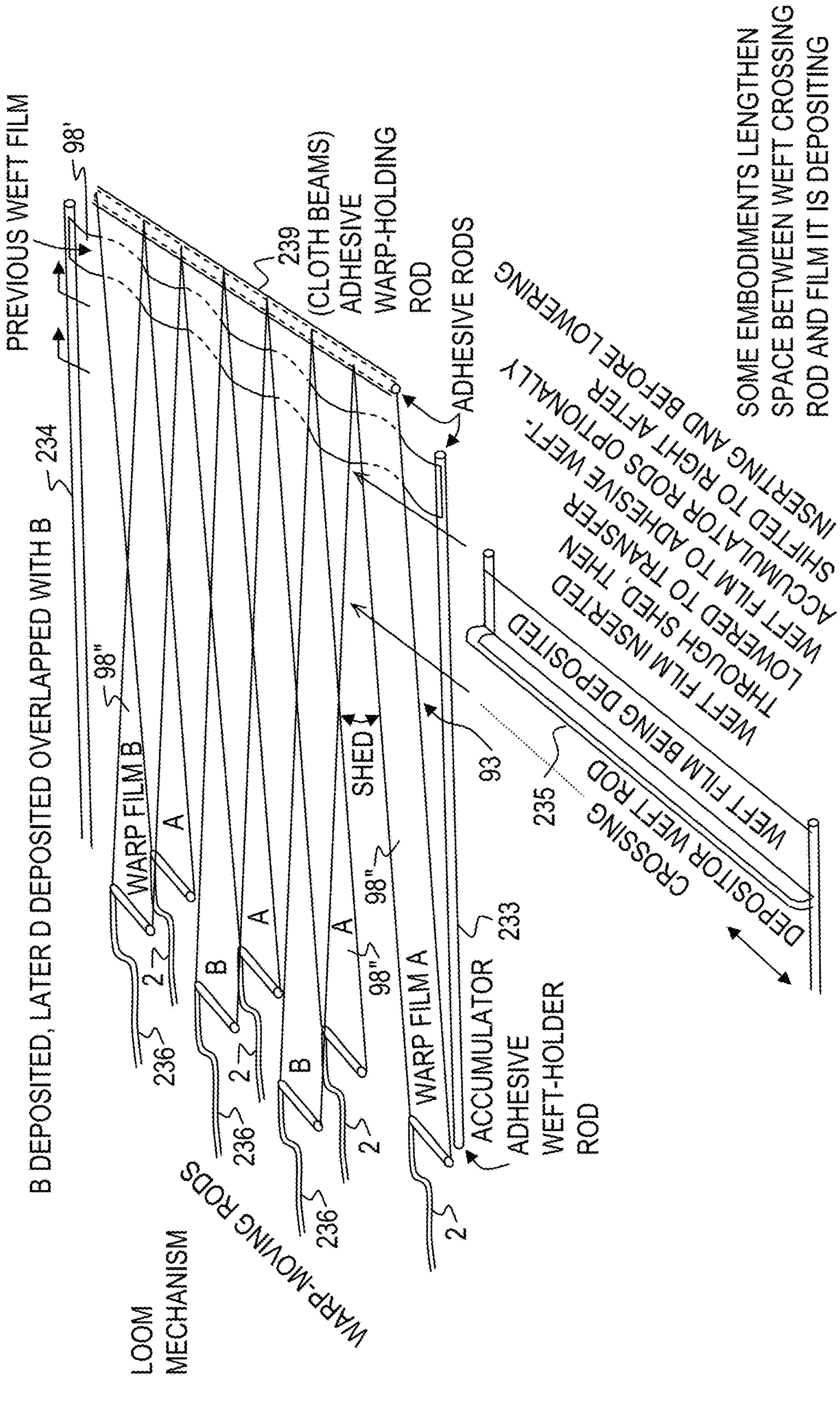

PREVIOUS WEFT FILM
98'
239
(CLOTH BEAMS)
ADHESIVE
WARP-HOLDING
ROD
ADHESIVE RODS
SOME EMBODIMENTS LENGTHEN
SPACE BETWEEN WEFT CROSSING
ROD AND FILM IT IS DEPOSITING
INSERTING AND BEFORE LOWERING
SHIFTED TO RIGHT AFTER
ACCUMULATOR RODS OPTIONALLY
WEFT FILM TO ADHESIVE WEFT-
LOWERED TO TRANSFER
THROUGH SHED, THEN
WEFT FILM INSERTED
WEFT FILM BEING DEPOSITED
WEFT ROD
CROSSING
DEPOSITOR WEFT ROD
235
93
234
B DEPOSITED, LATER D DEPOSITED OVERLAPPED WITH B
98"
WARP FILM B
A
SHED
B
2
236
WARP FILM A
ACCUMULATOR
ADHESIVE
WEFT-HOLDER
ROD
233
WARP-MOVING RODS
LOOM
MECHANISM

FIG. 2C

FIG. 2D

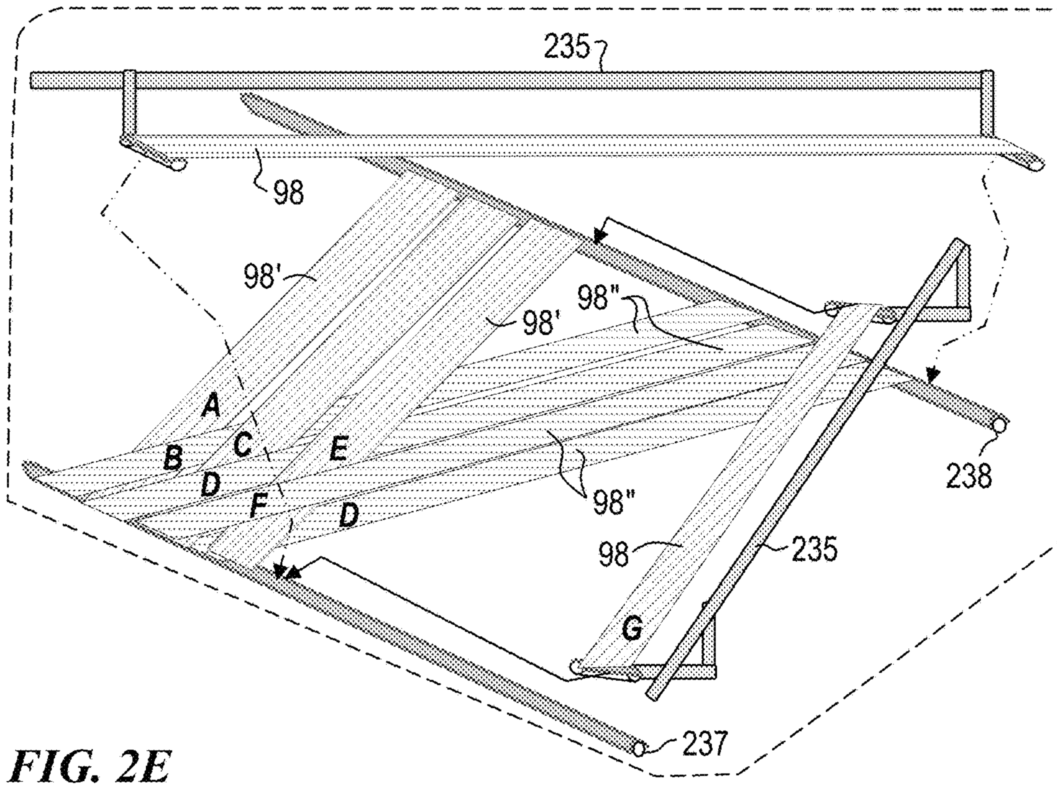

235
98
98'
98'
98"
A
B
C
D
E
F
D
98"
238
98
235
G
237

FIG. 2E

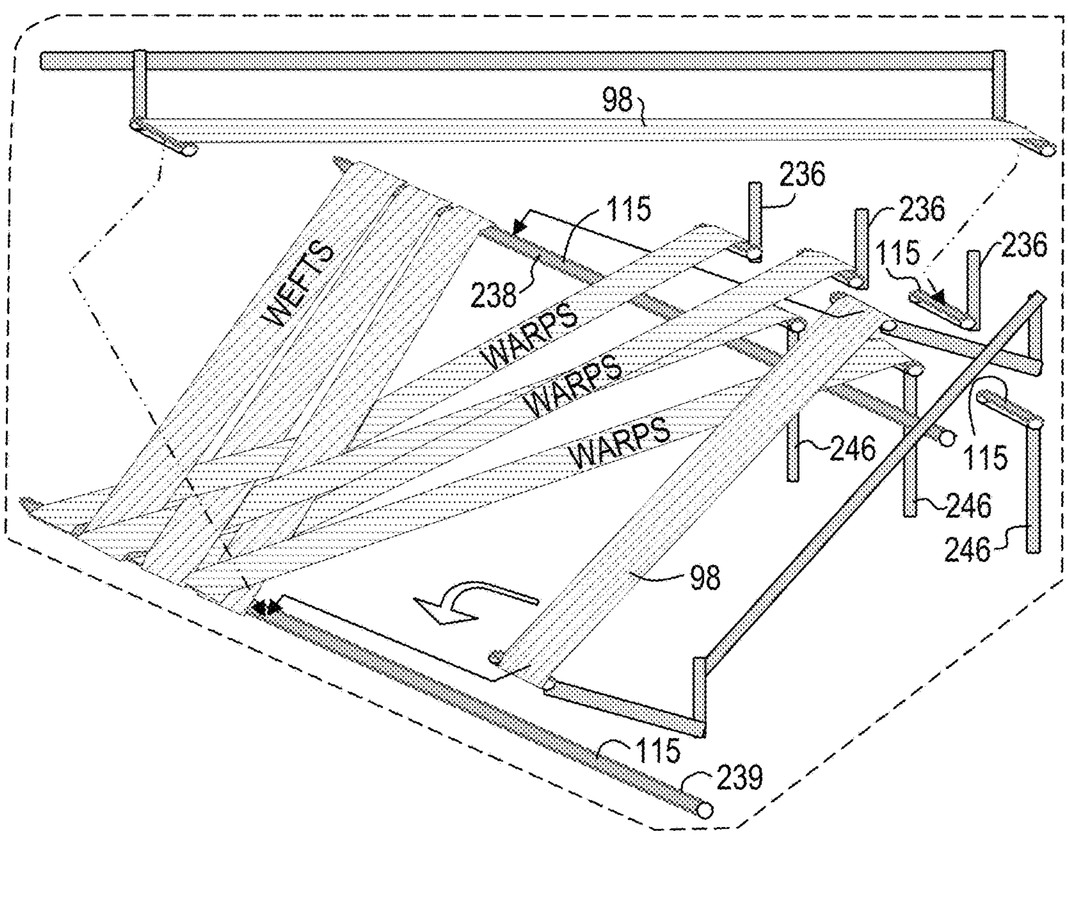

98
236
115
236
115
236
WEFTS
238
WARPS
WARPS
WARPS
246
115
246
246
98
115
239

FIG. 2F

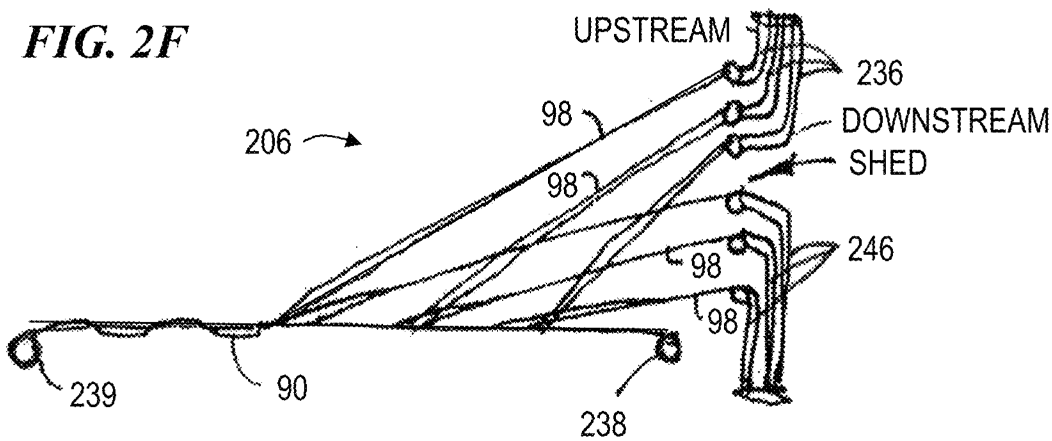


FIG. 3A

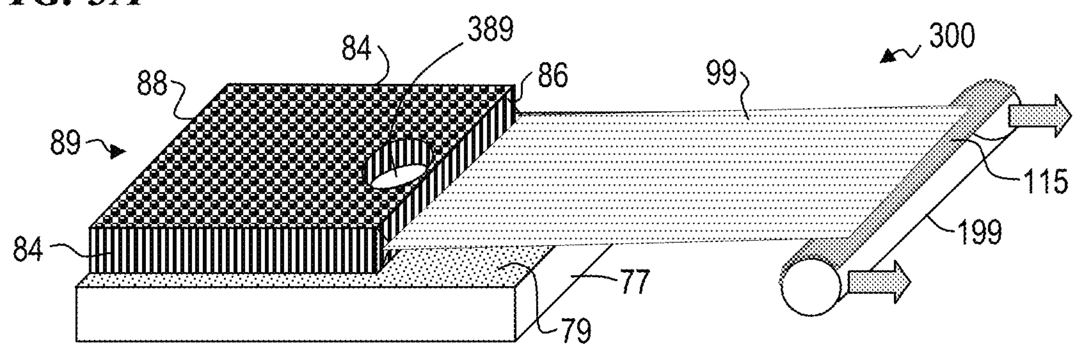
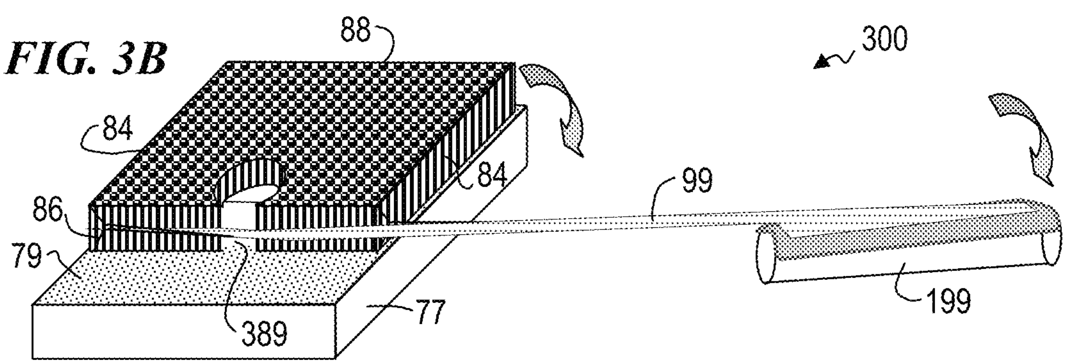
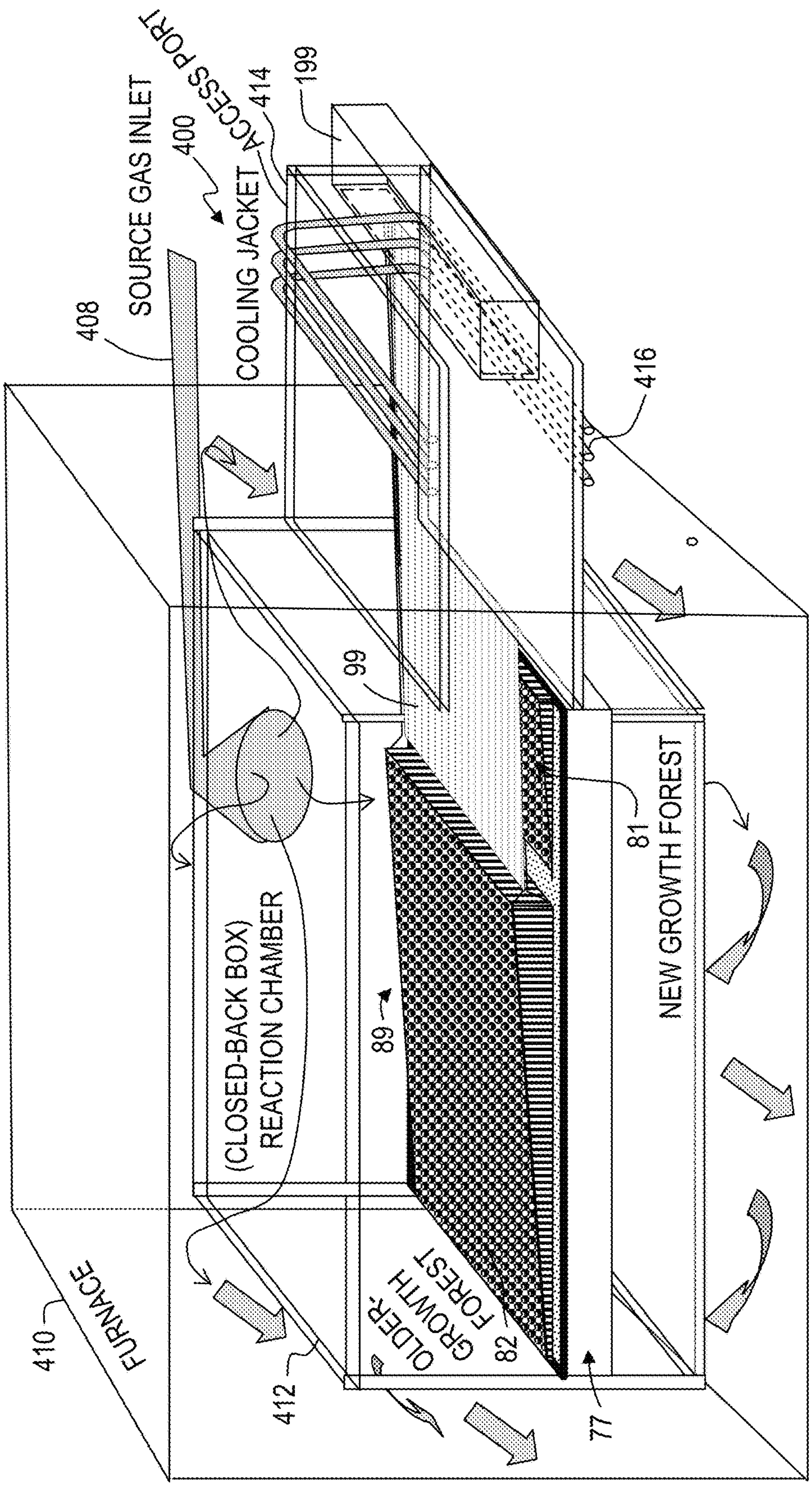


FIG. 3B





SOURCE GAS INLET
ACCESS PORT
COOLING JACKET
400
408
414
199
416
99
81
NEW GROWTH FOREST
(CLOSED-BACK BOX)
REACTION CHAMBER
89
OLDER-GROWTH FOREST
82
77
FURNACE
410
412

FIG. 4A

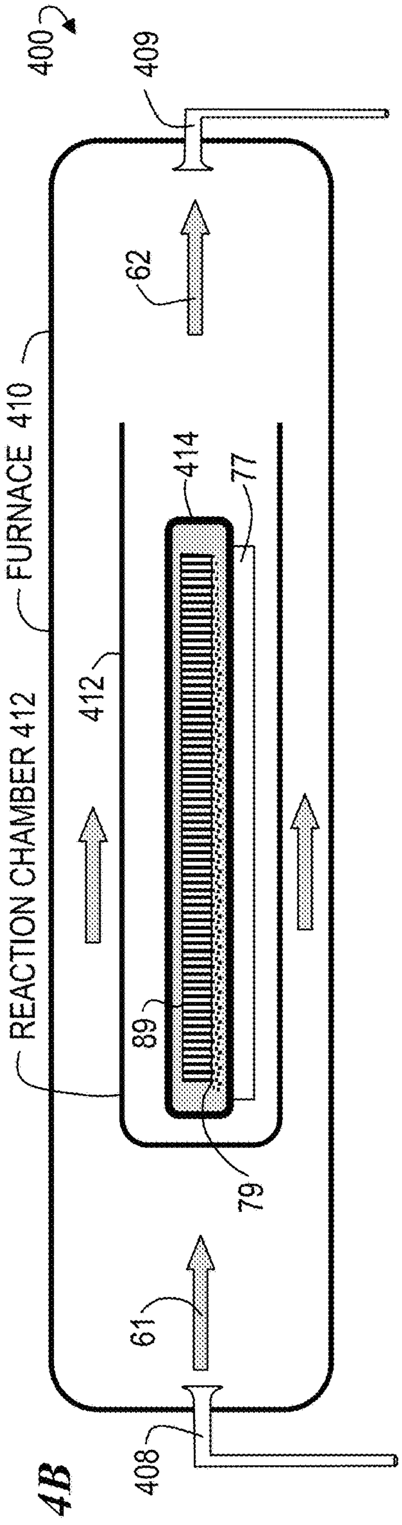

400
409
62
FURNACE 410
414
77
412
REACTION CHAMBER 412
89
79
61
408

FIG. 4B

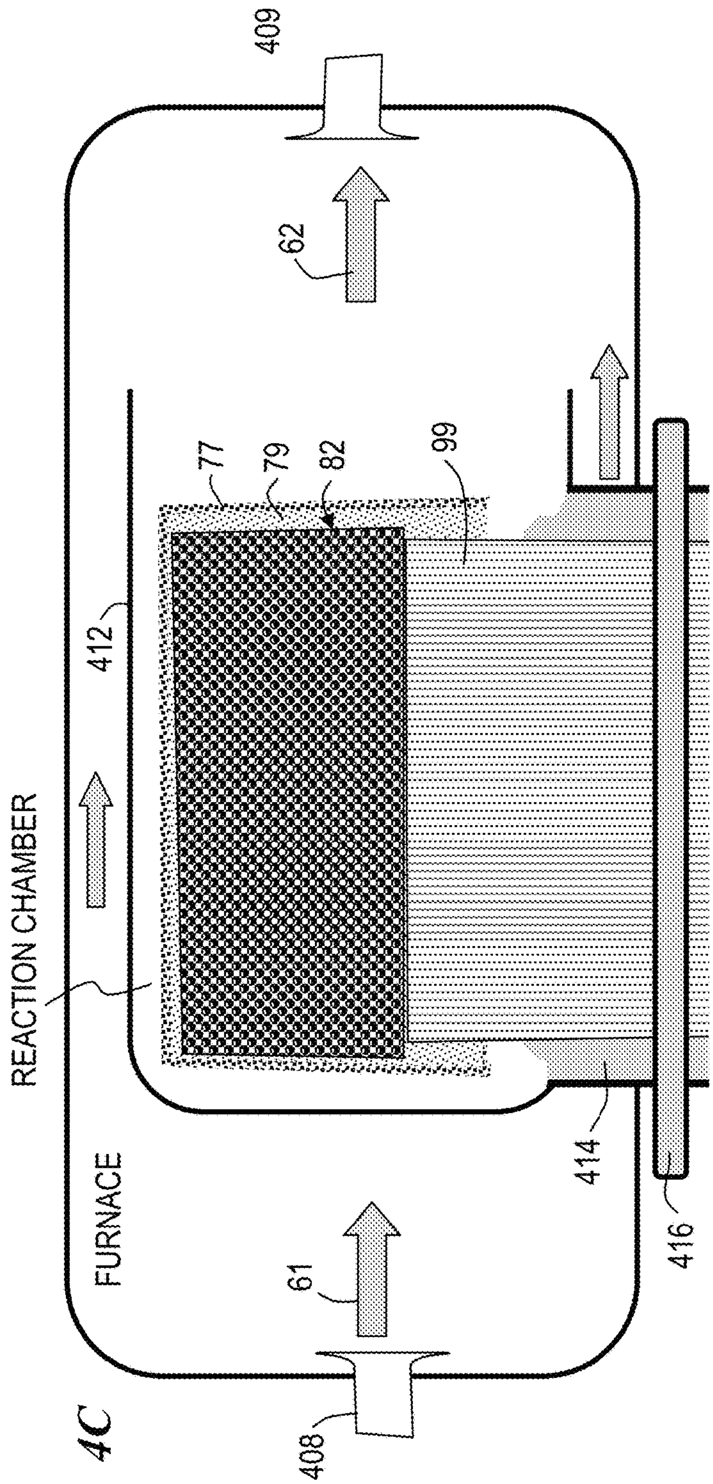

409
62
77
79
82
99
412
REACTION CHAMBER
414
FURNACE
416
61
408

FIG. 4C

FIG. 5A

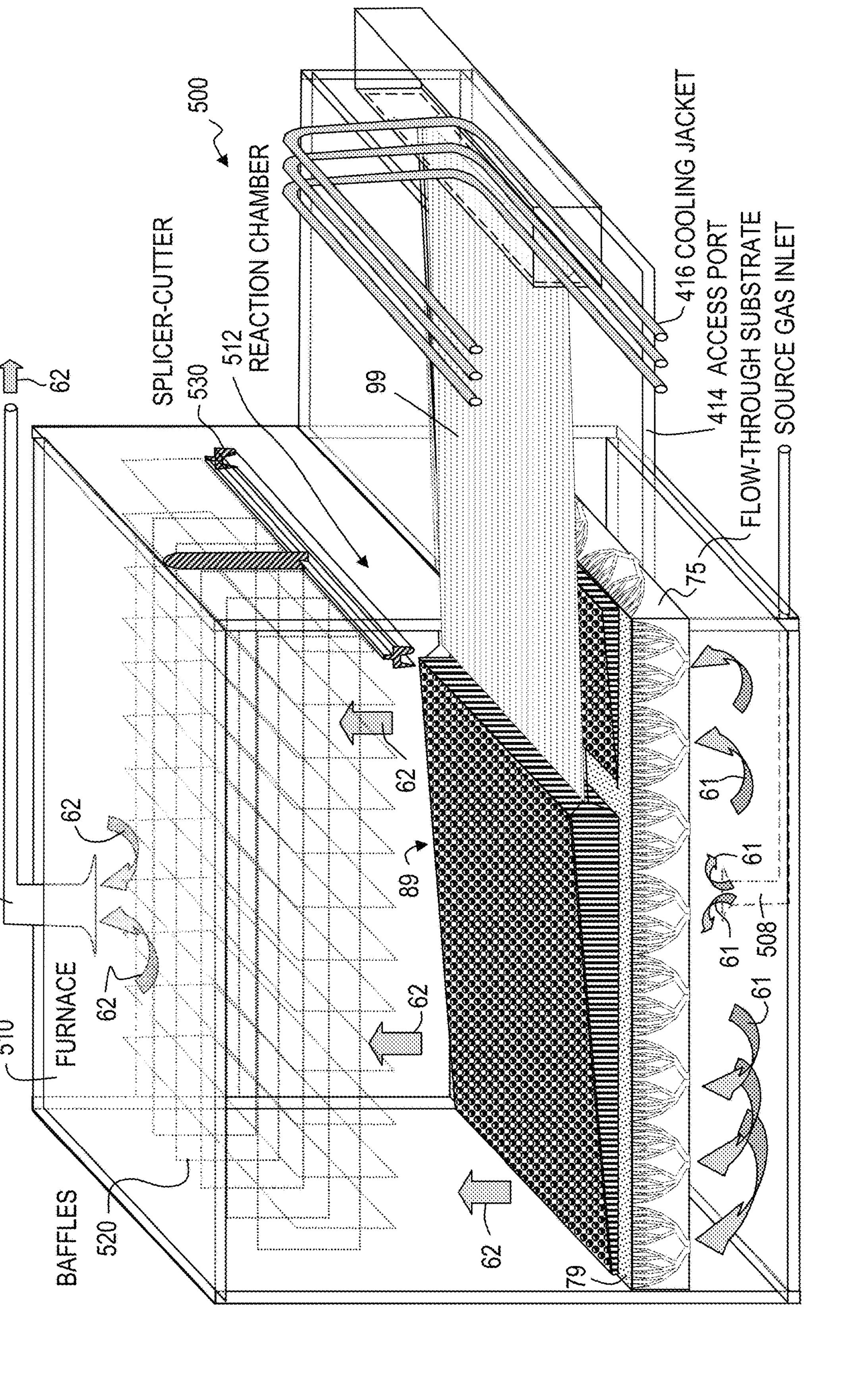
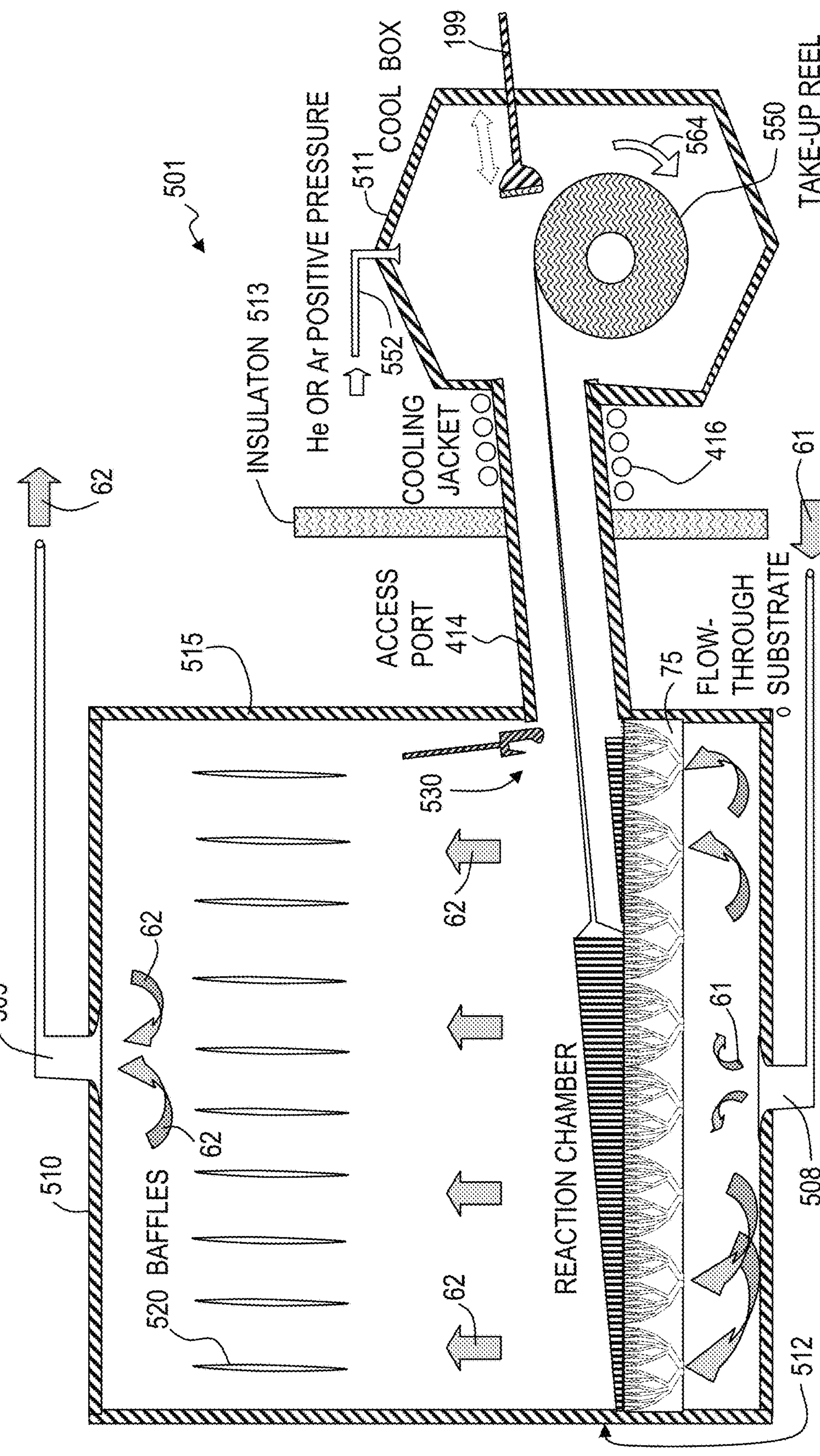

500
EXHAUST OUTLET
62
509
SPLICER-CUTTER
530
512
REACTION CHAMBER
416 COOLING JACKET
414 ACCESS PORT
FLOW-THROUGH SUBSTRATE
SOURCE GAS INLET
99
75
89
61
508
FURNACE
510
BAFFLES
520
79

FIG. 5B


501
199
COOL BOX
511
He OR Ar POSITIVE PRESSURE
552
564
550
TAKE-UP REEL
INSULATON 513
COOLING JACKET
416
62
61
ACCESS PORT 414
515
75
FLOW-THROUGH SUBSTRATE
530
62
509
62
61
62
510
520 BAFFLES
REACTION CHAMBER
508
62
512

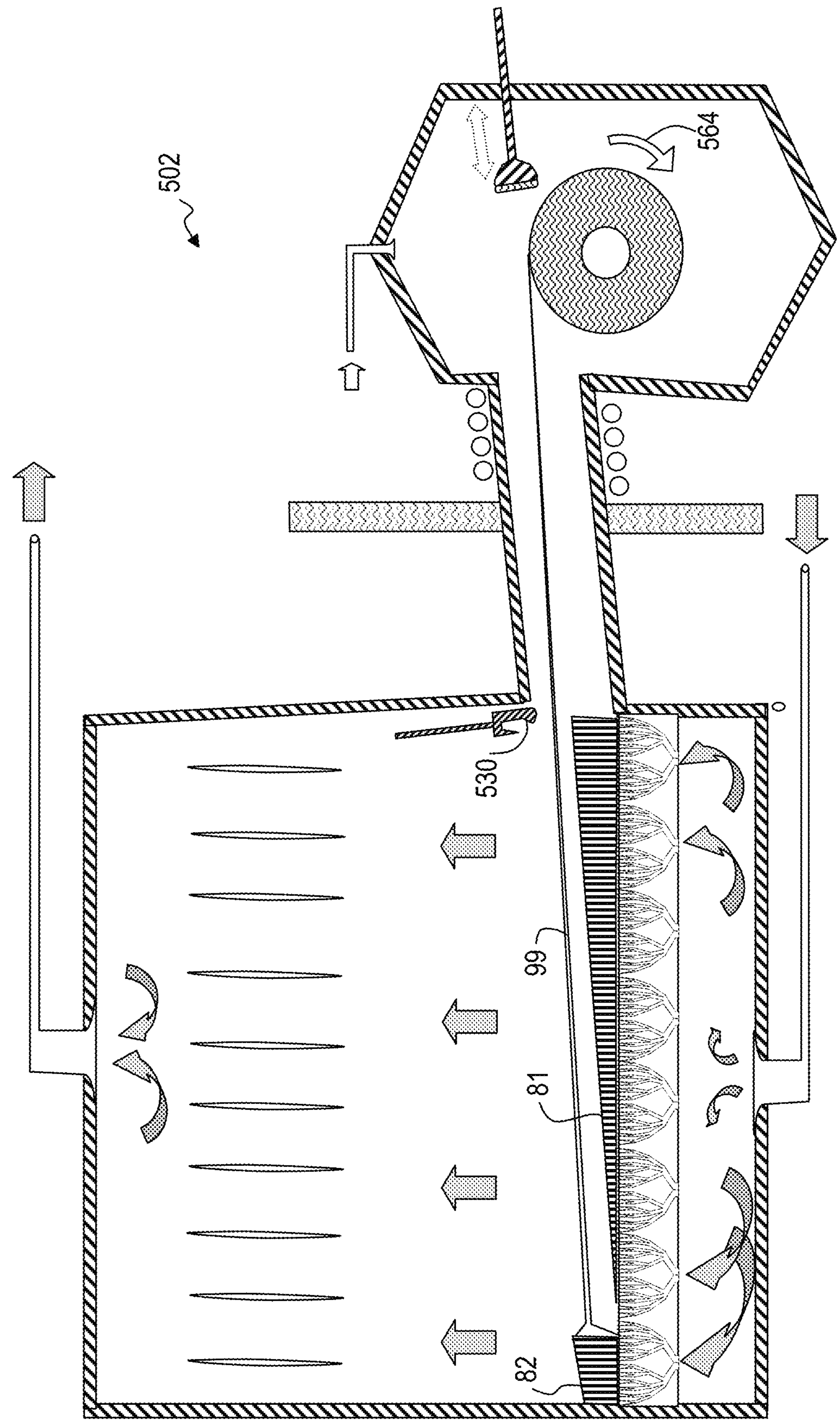
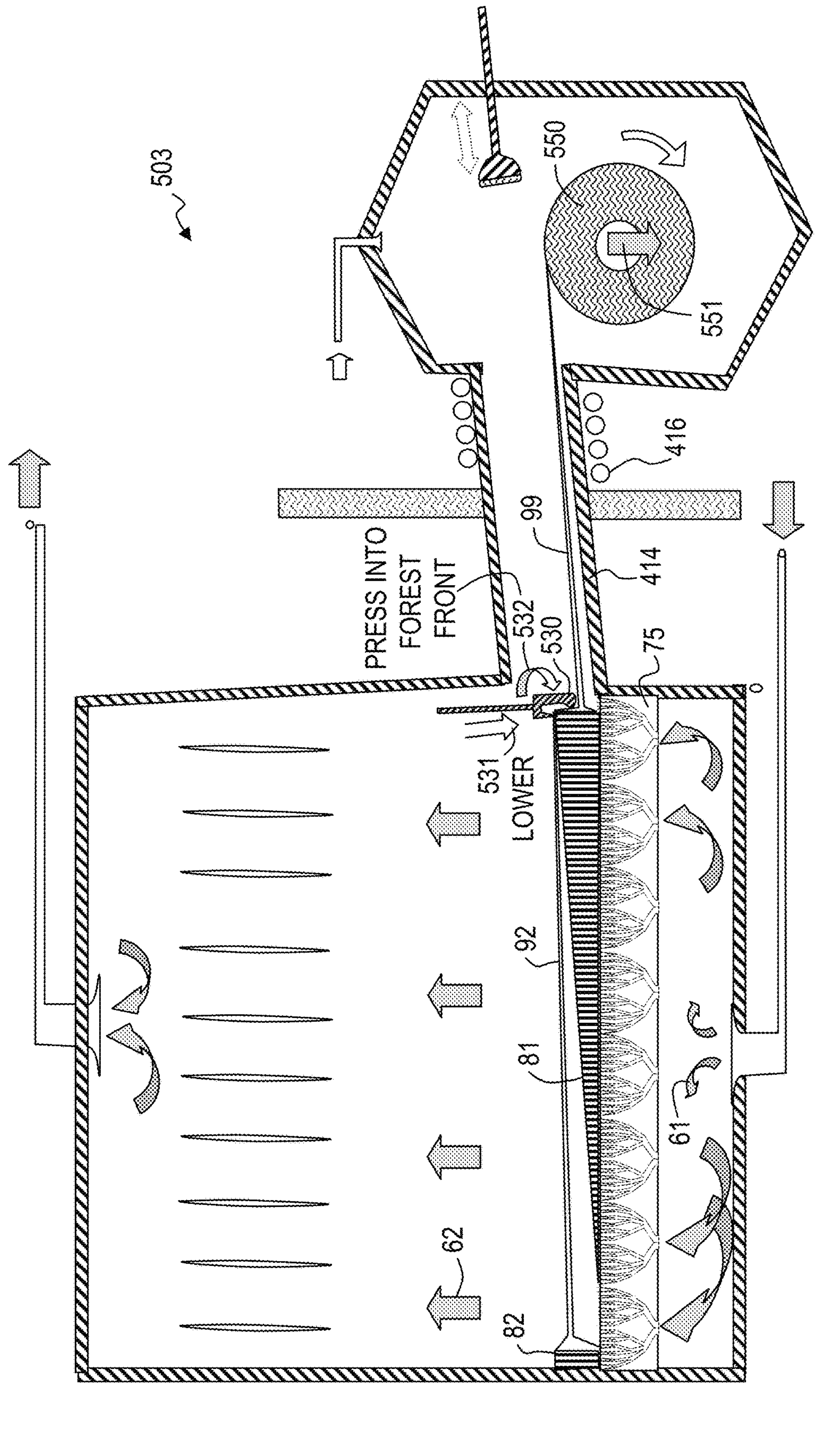


FIG. 5C

FIG. 5D



503
550
551
416
99
414
PRESS INTO FOREST FRONT
532
530
75
531
LOWER
92
81
61
62
82

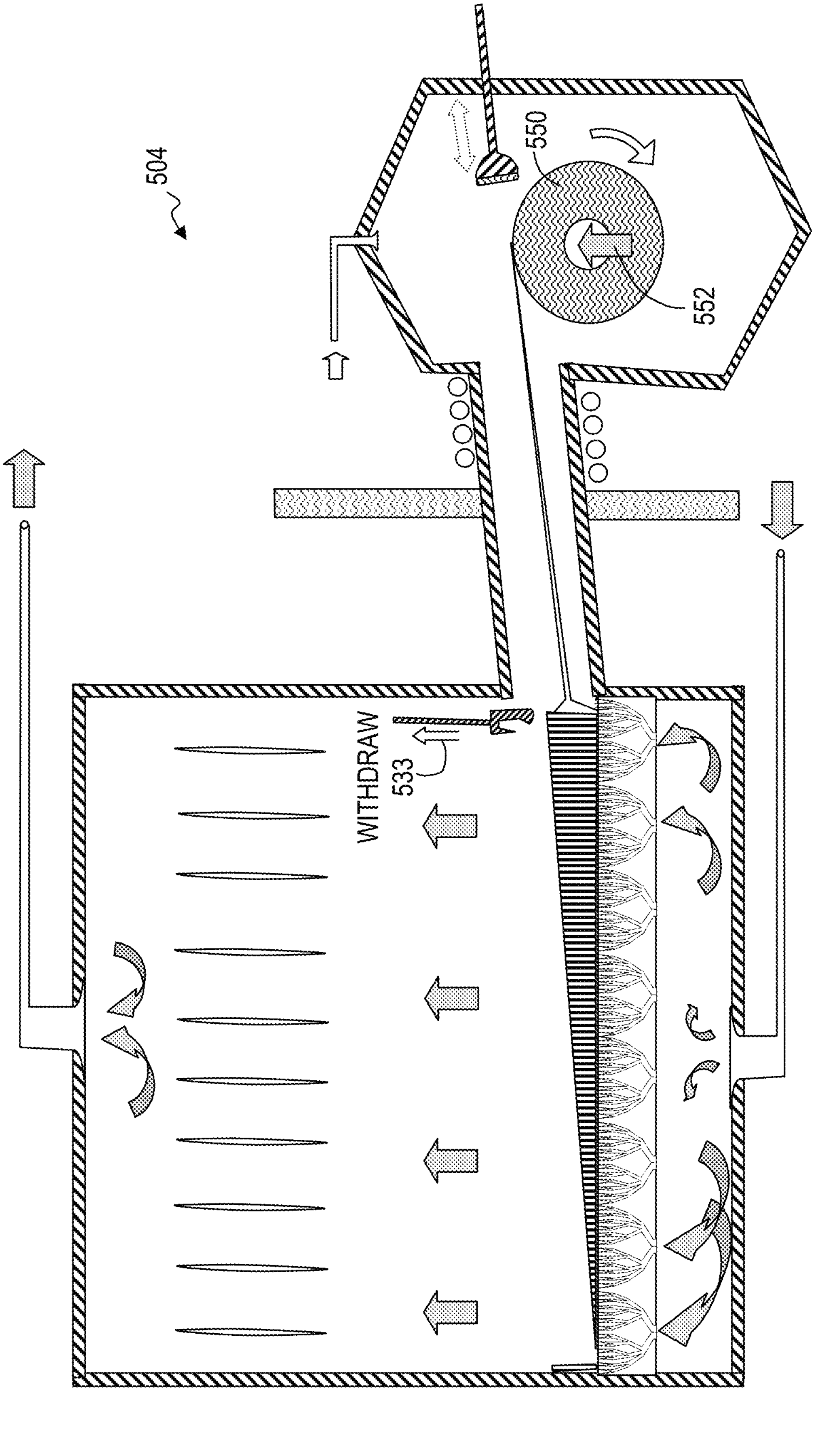


FIG. 5E

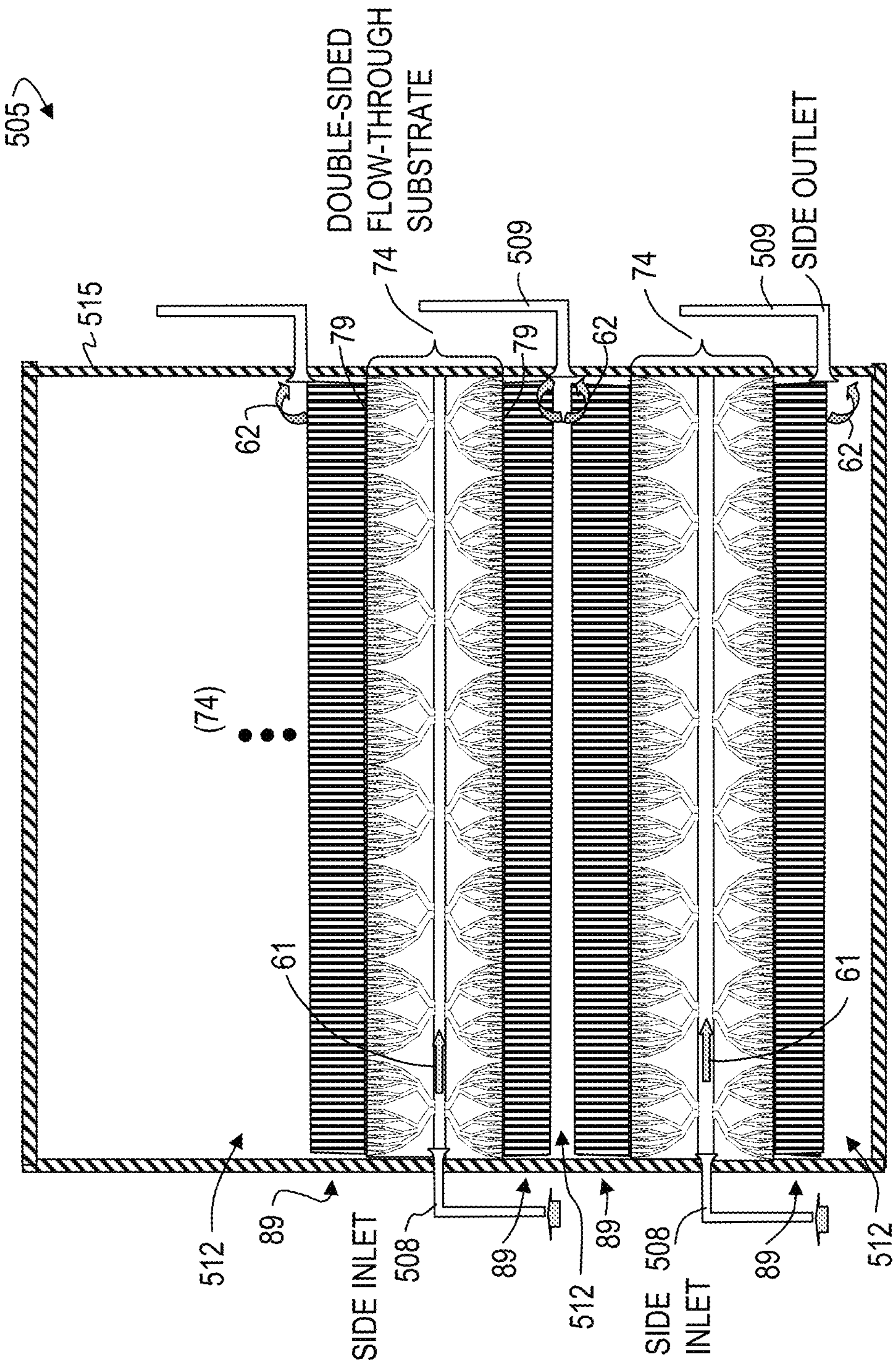

505
DOUBLE-SIDED FLOW-THROUGH SUBSTRATE
SIDE OUTLET
515
74
509
79
62
(74)
61
512
89
SIDE INLET
508
SIDE INLET

FIG. 5F

FIG. 5H

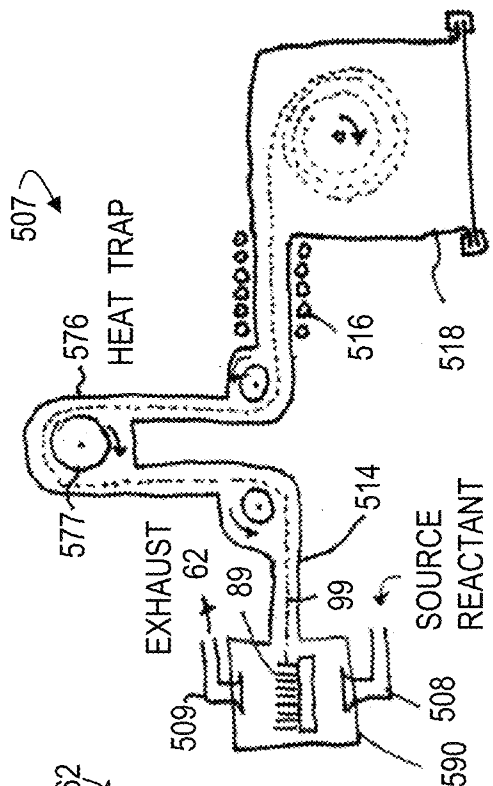

507
HEAT TRAP
576
577
516
518
514
EXHAUST
62
89
99
SOURCE
REACTANT
GASSES 61
509
508
590

FIG. 5G

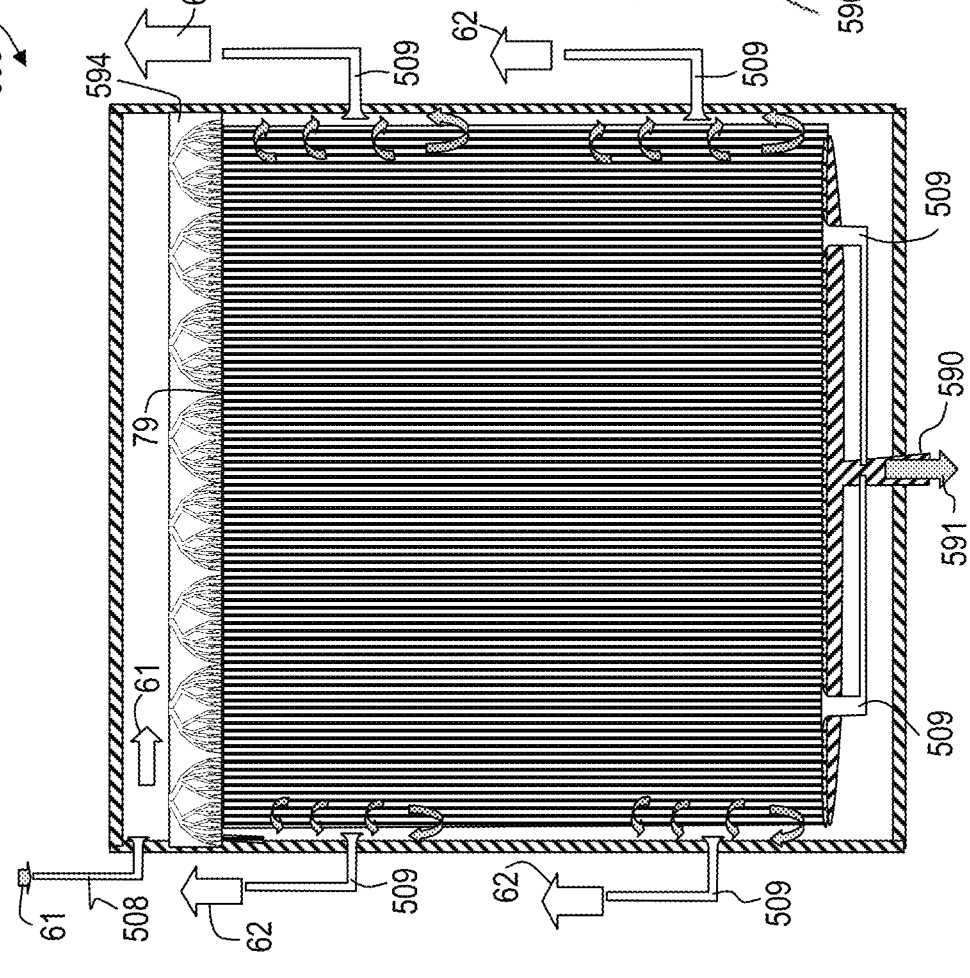

506
594
62
509
79
590
591
61
508

FIG. 6A

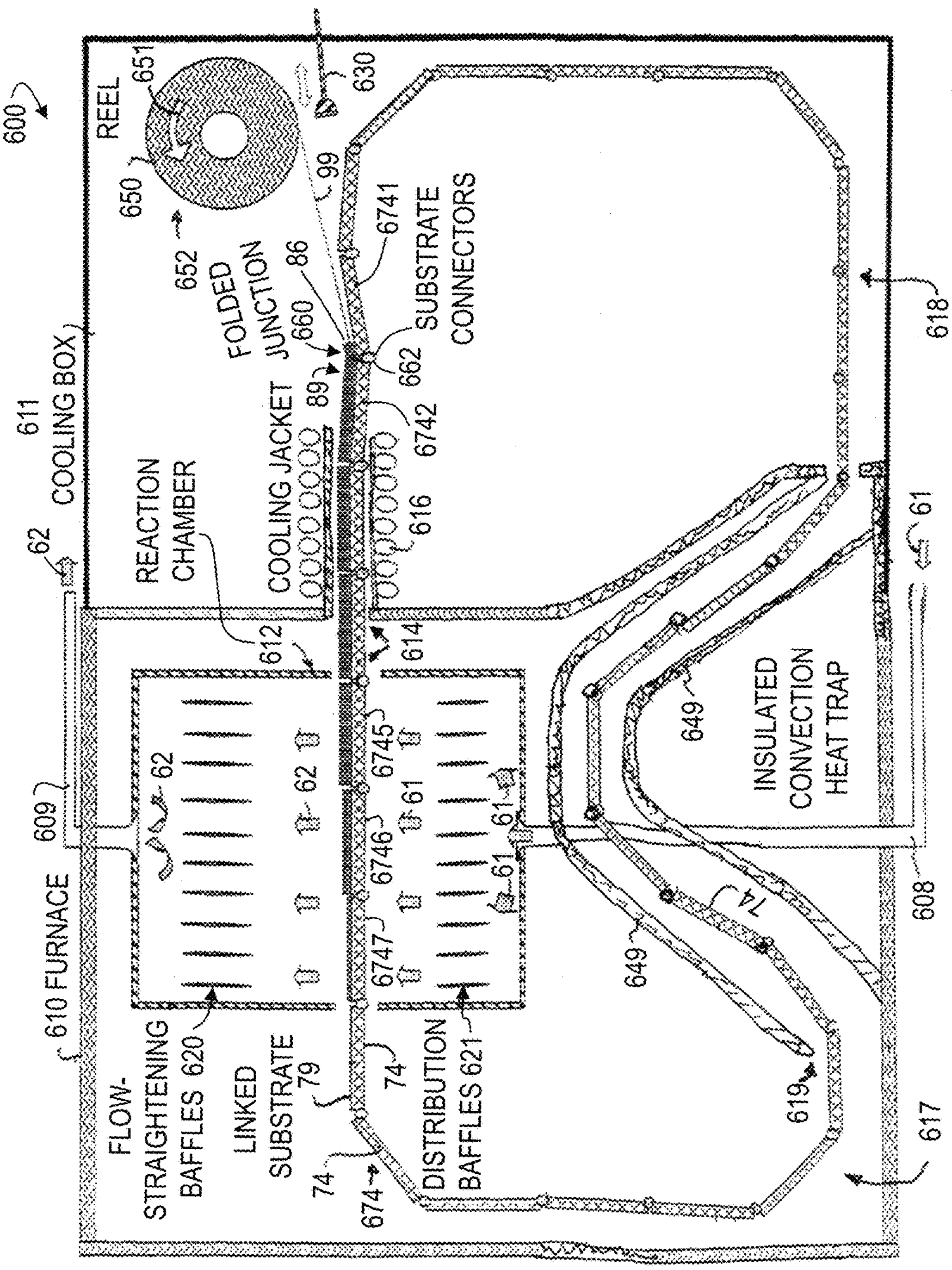
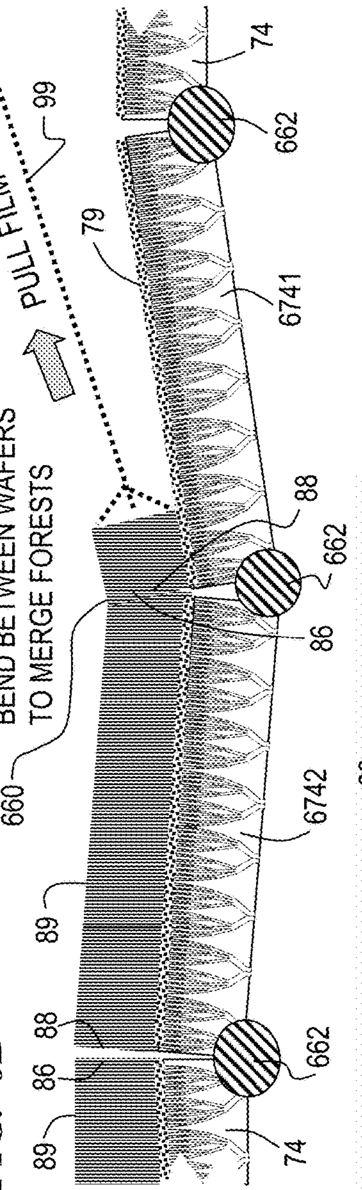
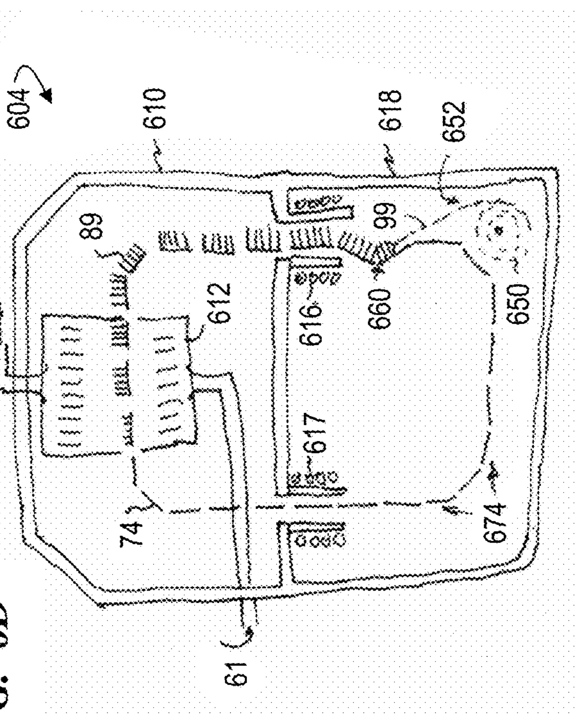

600
REEL
651
630
650
652
99
6741
SUBSTRATE
CONNECTORS
FOLDED
JUNCTION
86
660
662
89
6742
611
COOLING BOX
REACTION
CHAMBER
COOLING JACKET
616
62
61
612
614
618
6745
6746
6747
609
610 FURNACE
FLOW-
STRAIGHTENING
BAFFLES 620
LINKED
SUBSTRATE
79
74
674
DISTRIBUTION
BAFFLES 621
649
INSULATED
CONVECTION
HEAT TRAP
608
619
617

FIG. 6B



FOLDED JUNCTION = BEND BETWEEN WAFERS TO MERGE FORESTS
PULL FILM
99
79
74
662
6741
88
662
86
660
6742
89
88
86
89
662
74

FIG. 6D



604
610
618
652
89
99
62
612
616
660
650
617
74
674
61

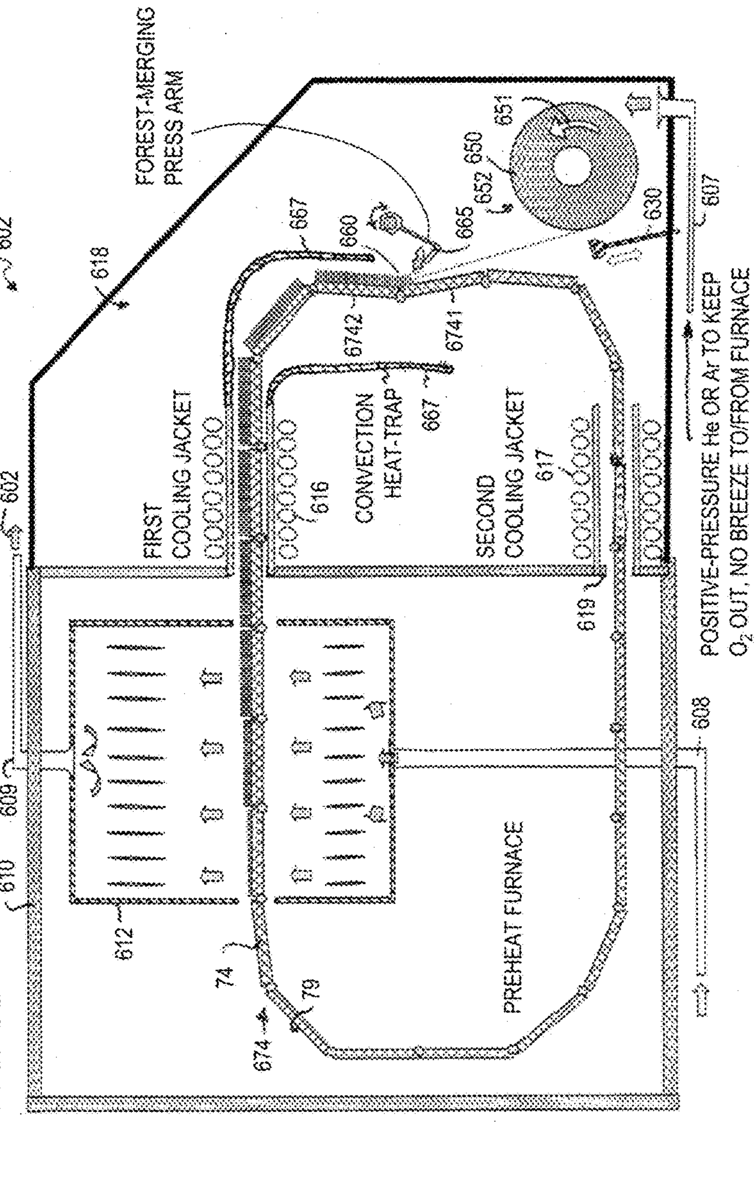
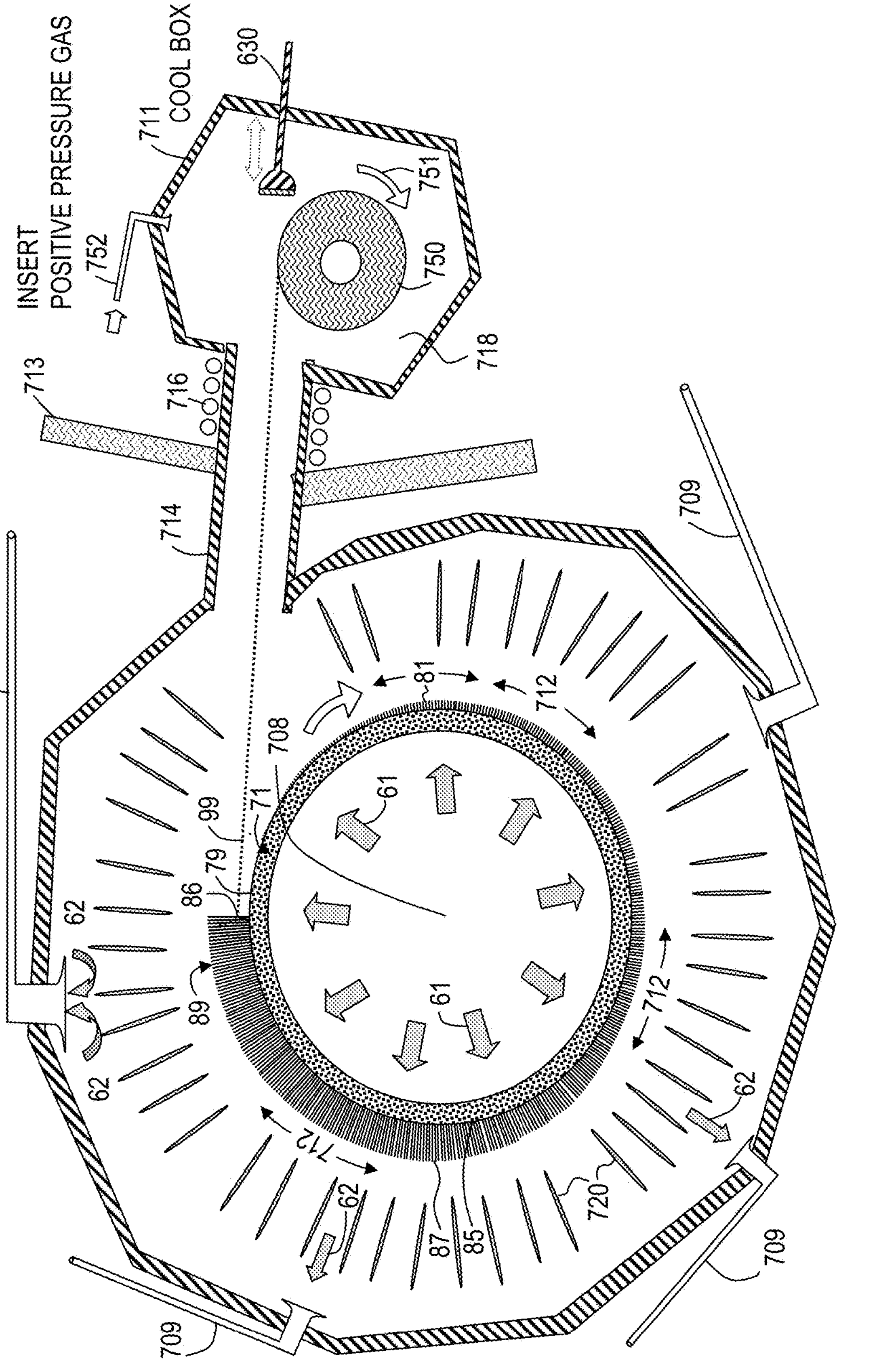

FOREST-MERGING PRESS ARM
602
618
667
660
665
651
650
652
630
607
6742
6741
CONVECTION HEAT-TRAP
667
FIRST COOLING JACKET
616
SECOND COOLING JACKET
617
602
619
POSITIVE-PRESSURE He OR Ar TO KEEP O_2 OUT, NO BREEZE TO/FROM FURNACE
608
609
610
612
74
79
674
PREHEAT FURNACE

FIG. 6C

FIG. 7A



700
INSERT
POSITIVE PRESSURE GAS
752
711
COOL BOX
630
751
750
718
713
716
714
709
708
99
71
79
86
62
89
61
81
712
87
85
720

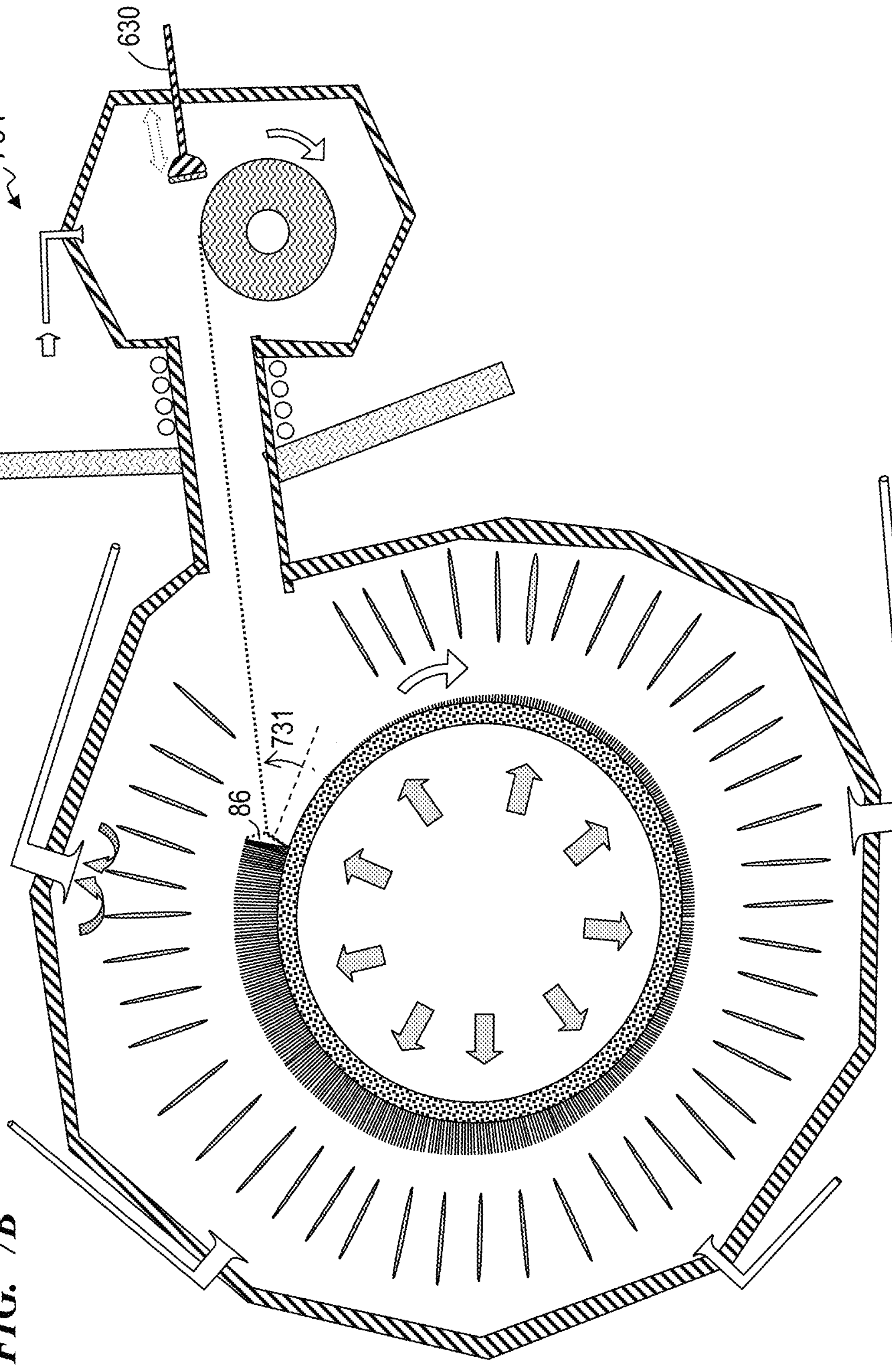


FIG. 7B

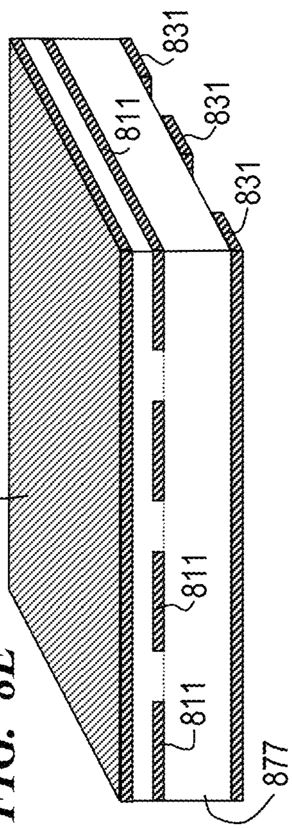


FIG. 8E

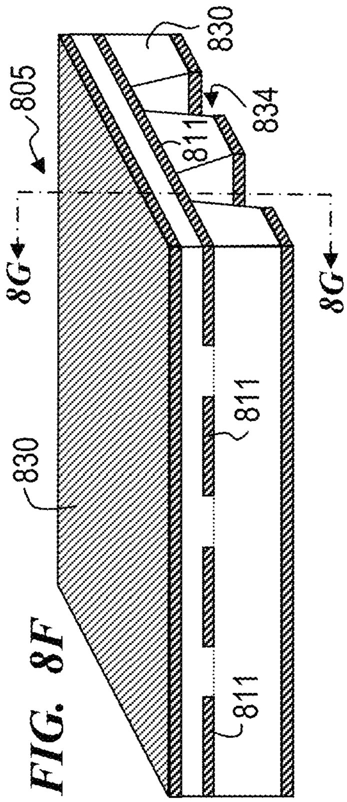


FIG. 8F

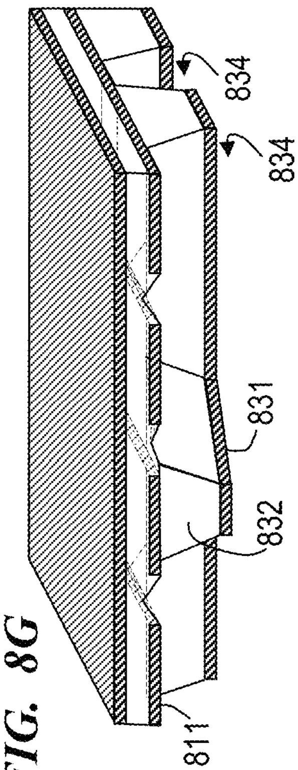


FIG. 8G

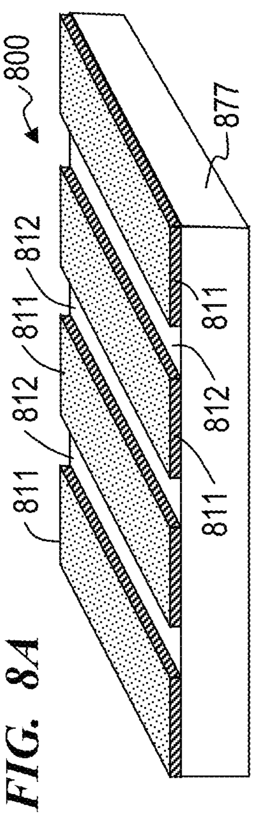


FIG. 8A

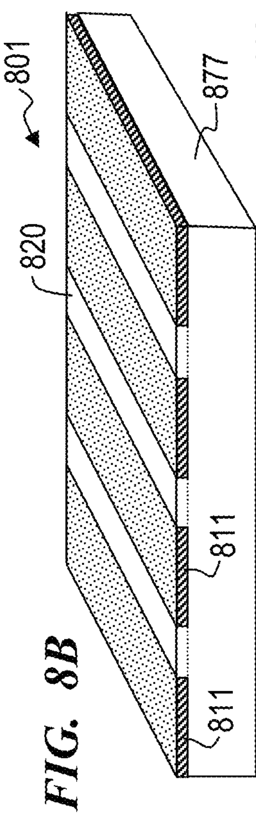


FIG. 8B

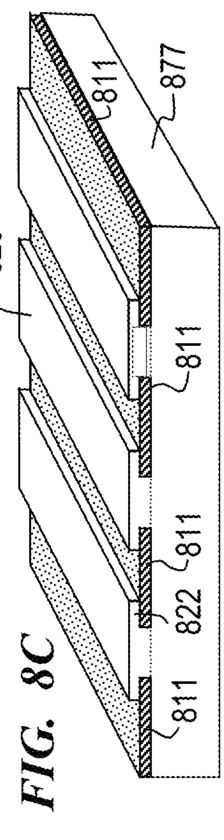


FIG. 8C

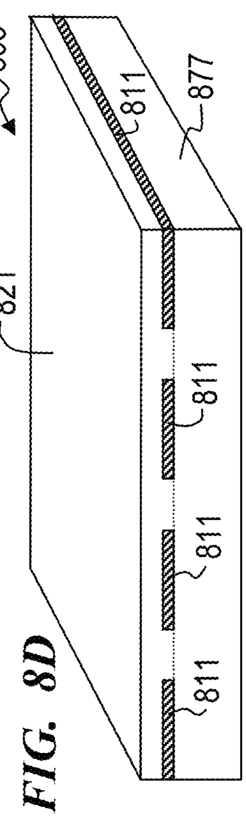


FIG. 8D

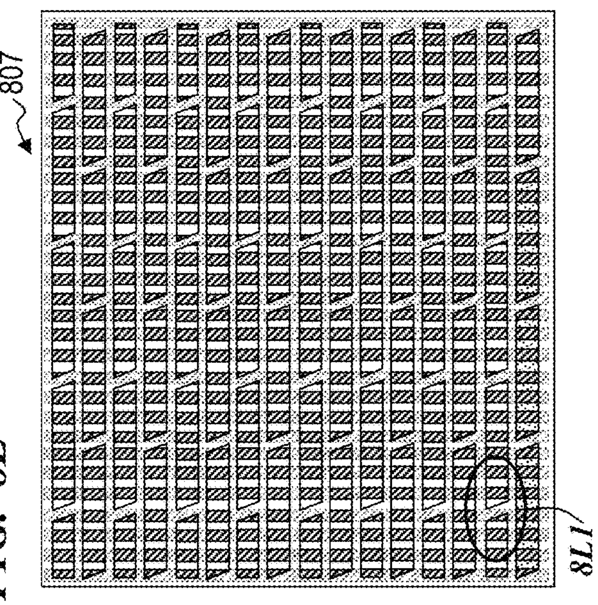


FIG. 8L

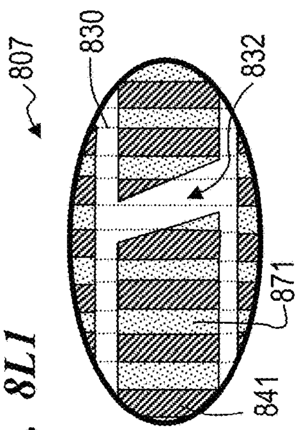


FIG. 8L1

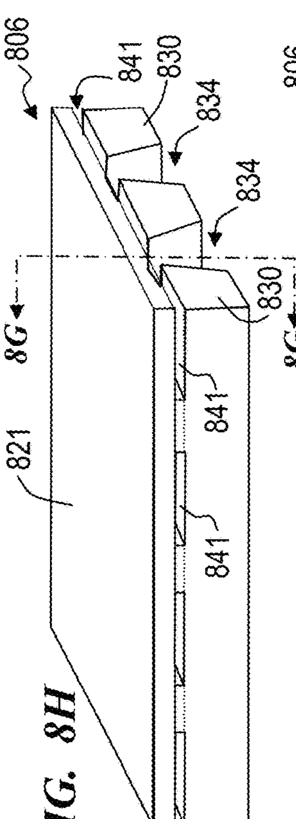


FIG. 8H

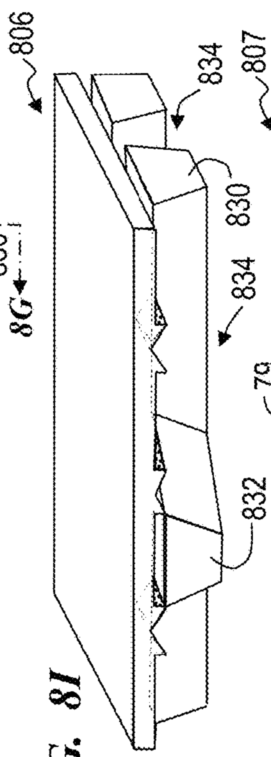


FIG. 8I

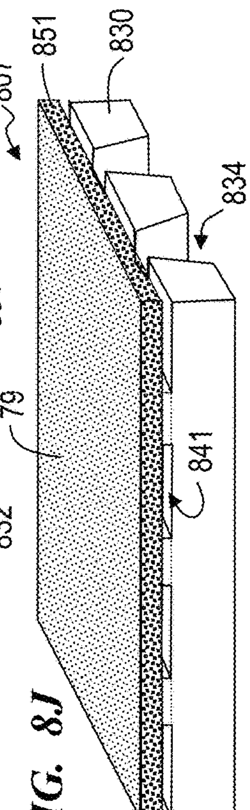


FIG. 8J

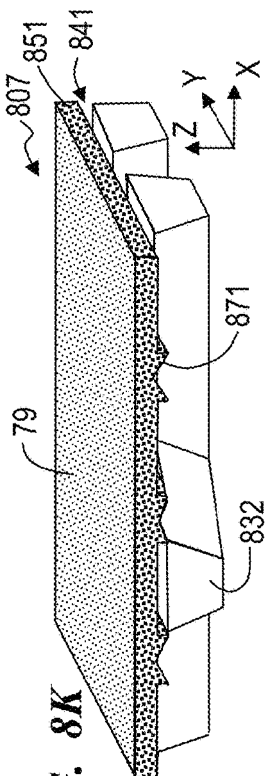


FIG. 8K

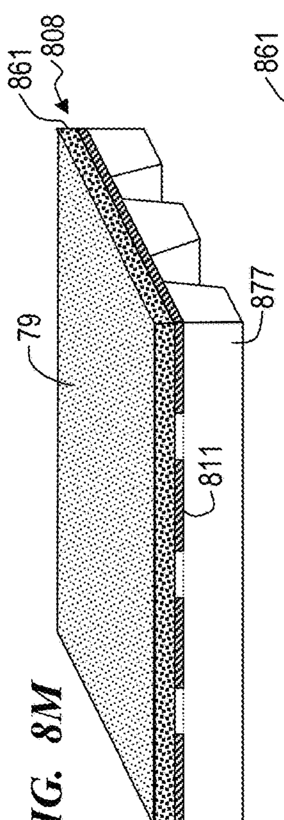


FIG. 8M

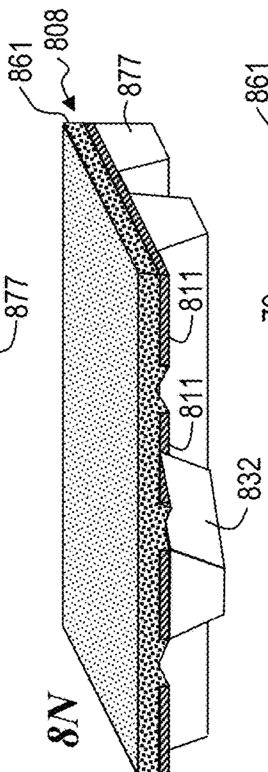


FIG. 8N

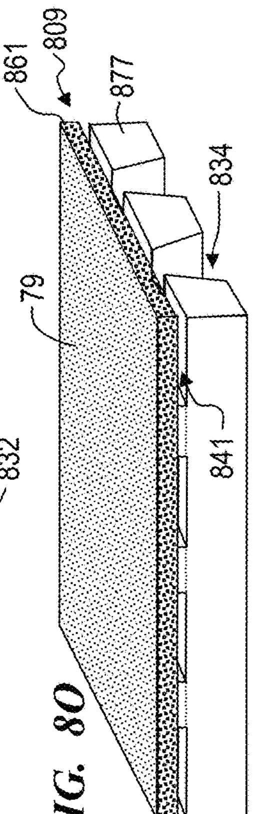


FIG. 8O

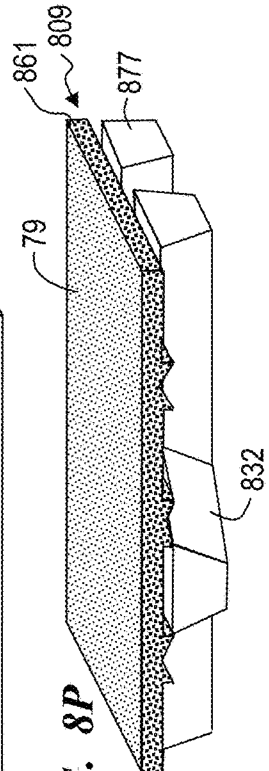


FIG. 8P

FIG. 9A

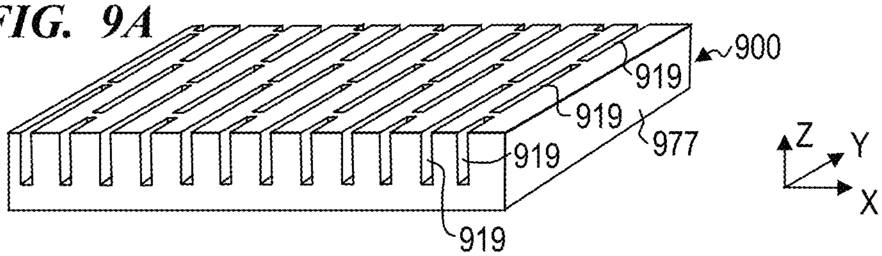


FIG. 9B

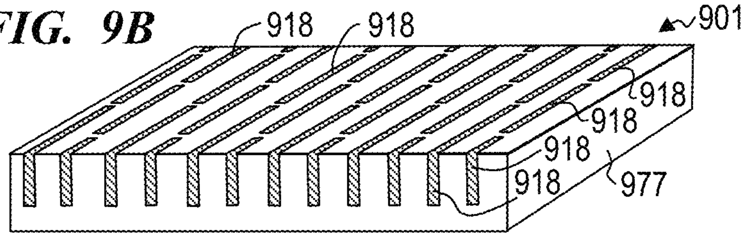


FIG. 9C

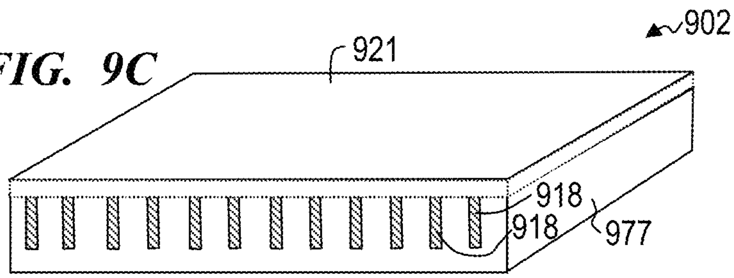


FIG. 9D

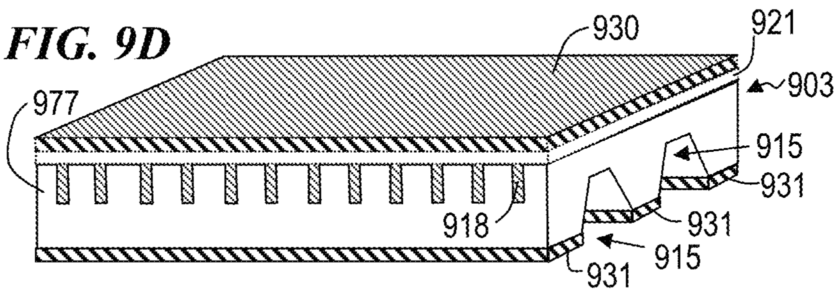


FIG. 9E

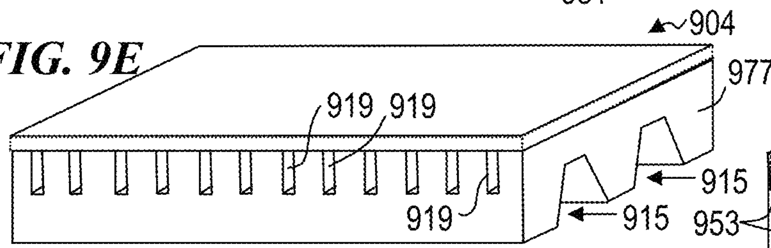


FIG. 9F

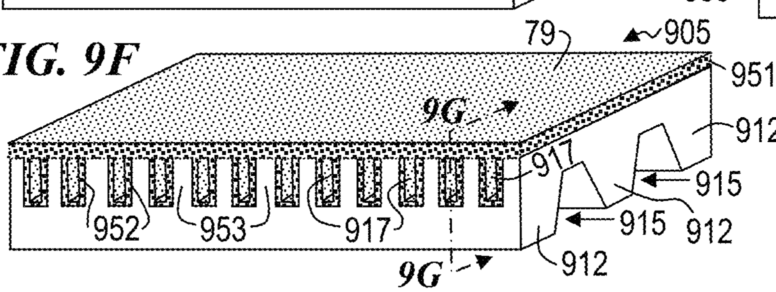
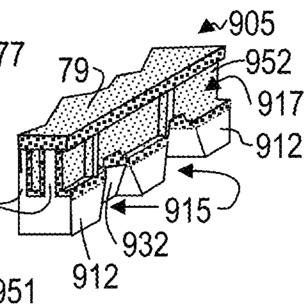


FIG. 9G



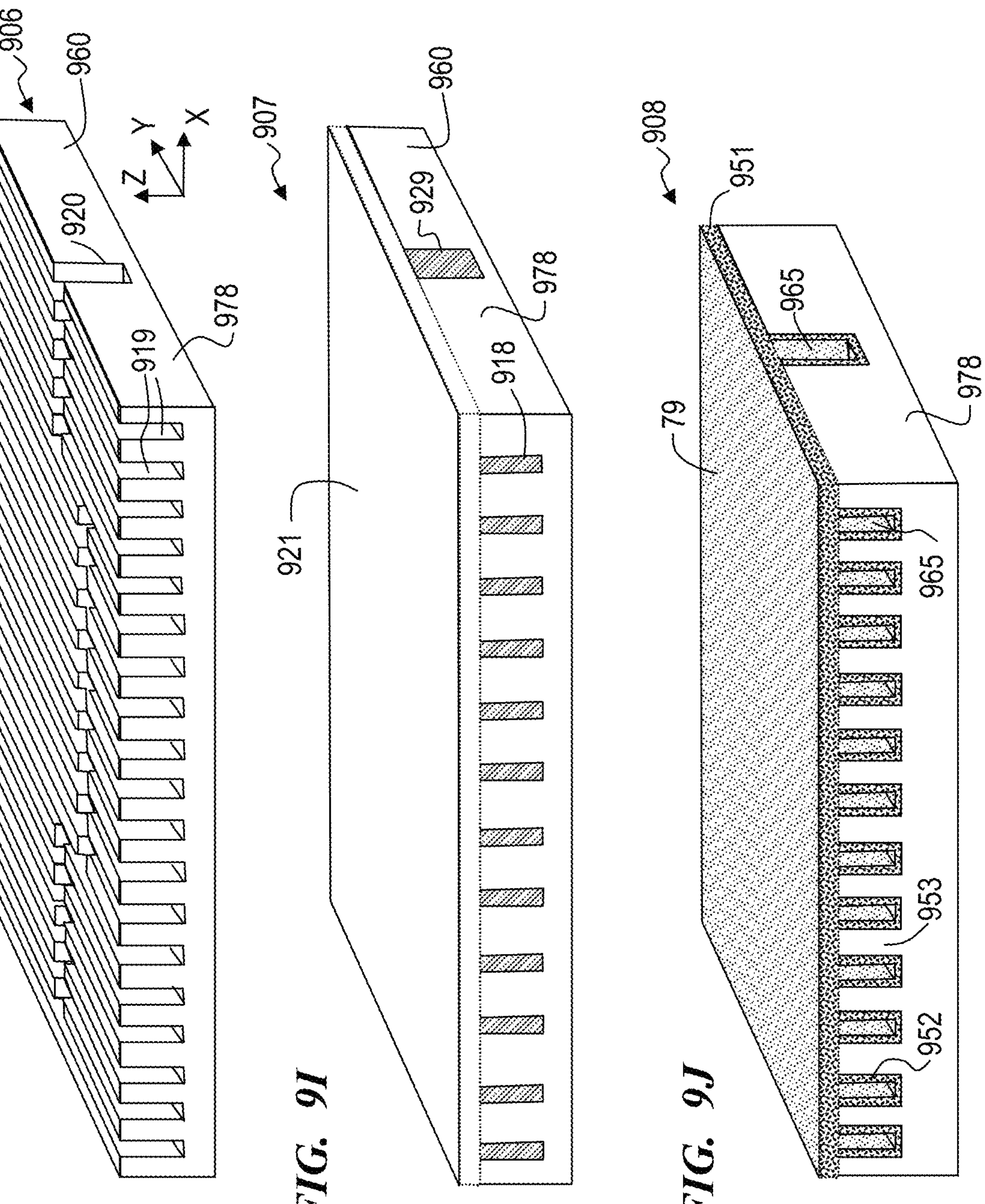


FIG. 9H

FIG. 9I

FIG. 9J

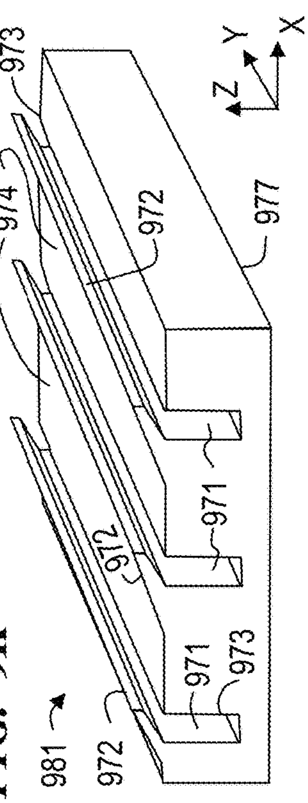


FIG. 9K

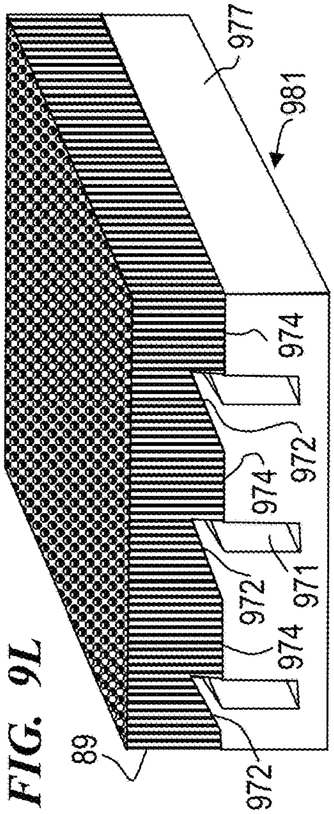


FIG. 9L

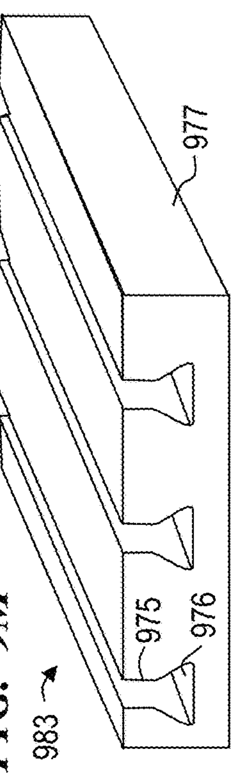


FIG. 9M

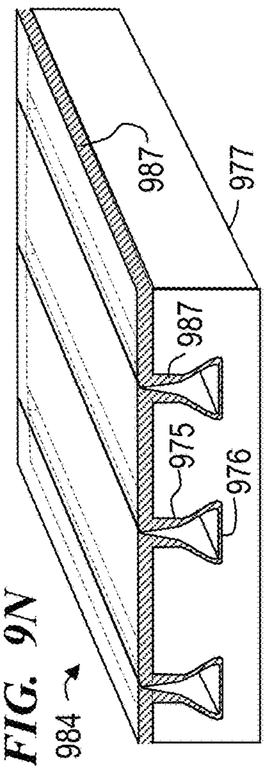


FIG. 9N

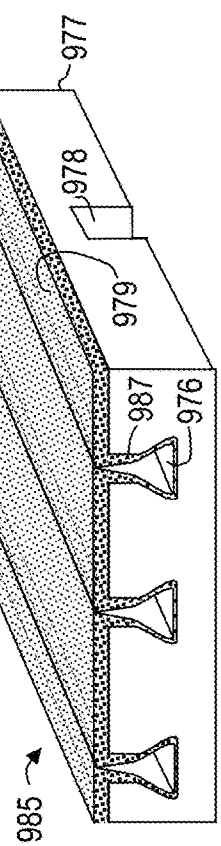


FIG. 9O

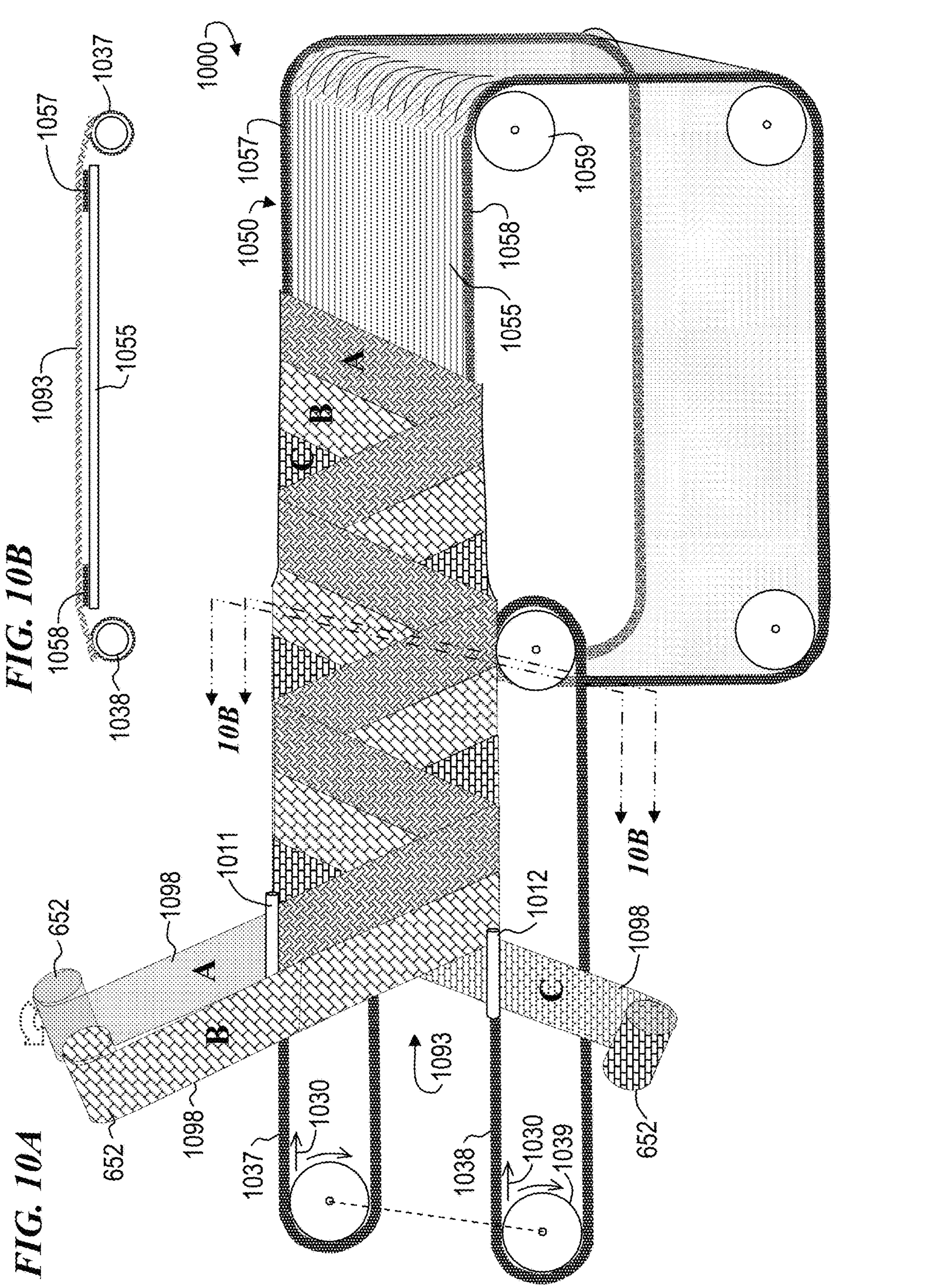


FIG. 10B
1057
1037
1093
1055
1058
1038
1000
1050
1057
1059
1058
1055
A
B
C
10B
10B
1011
1012
1098
652
A
B
C
1093
1030
1037
1038
1039
652
FIG. 10A

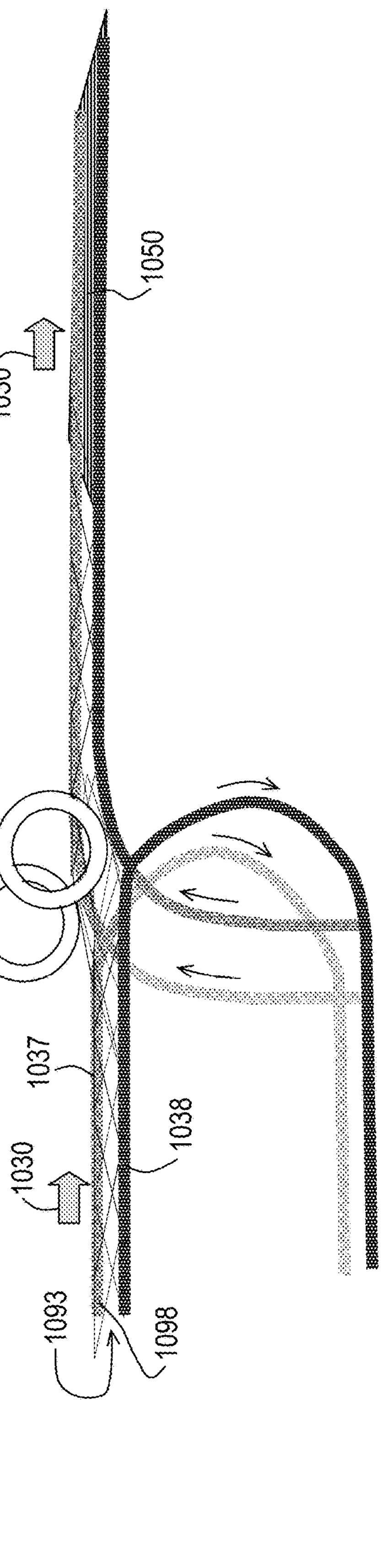


FIG. 10C

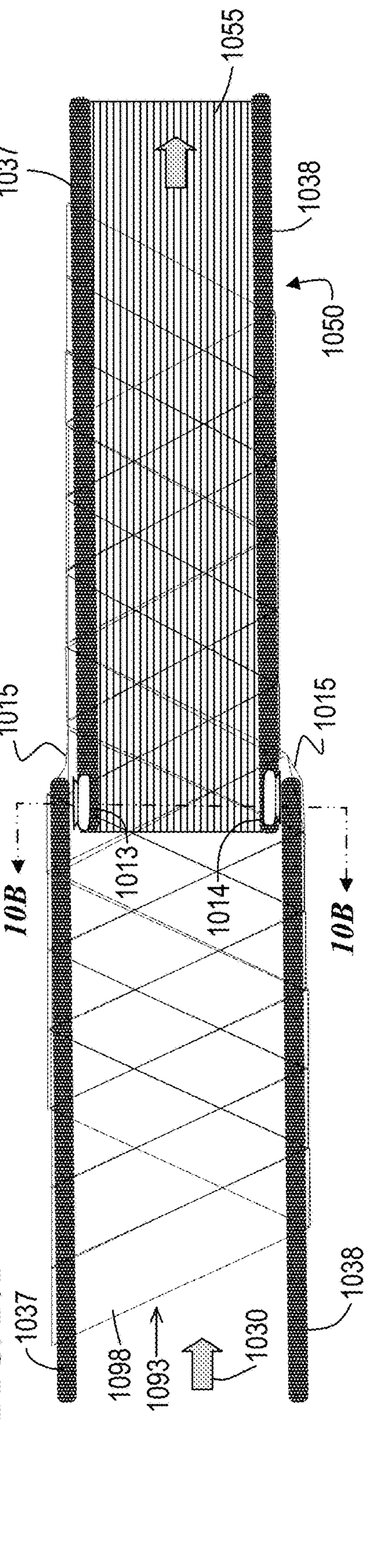


FIG. 10D

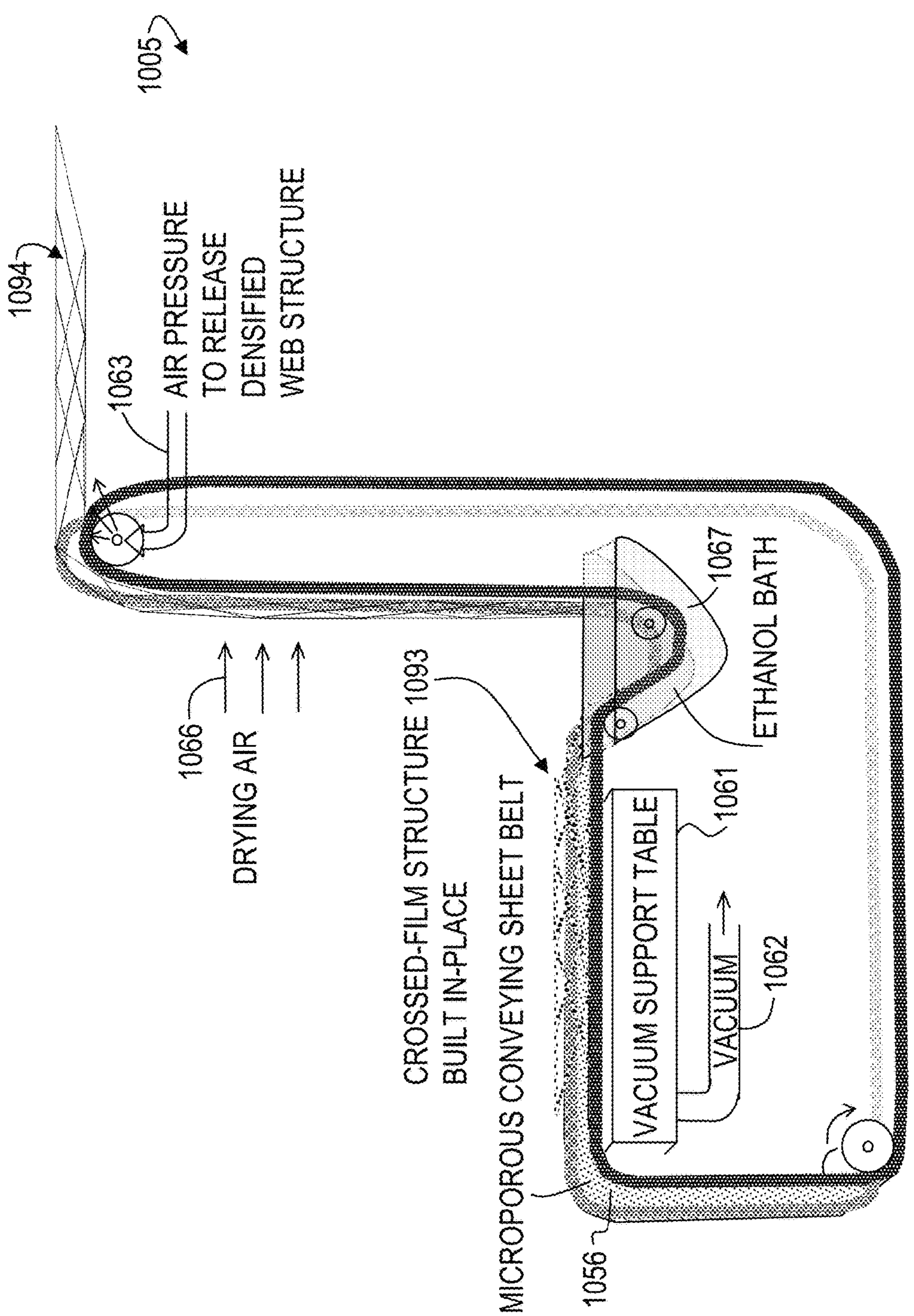

1005
1094
1063
AIR PRESSURE
TO RELEASE
DENSIFIED
WEB STRUCTURE
1066
DRYING AIR
CROSSED-FILM STRUCTURE 1093
BUILT IN-PLACE
MICROPOROUS CONVEYING SHEET BELT
1056
1067
ETHANOL BATH
1061
VACUUM SUPPORT TABLE
VACUUM
1062

FIG. 10E

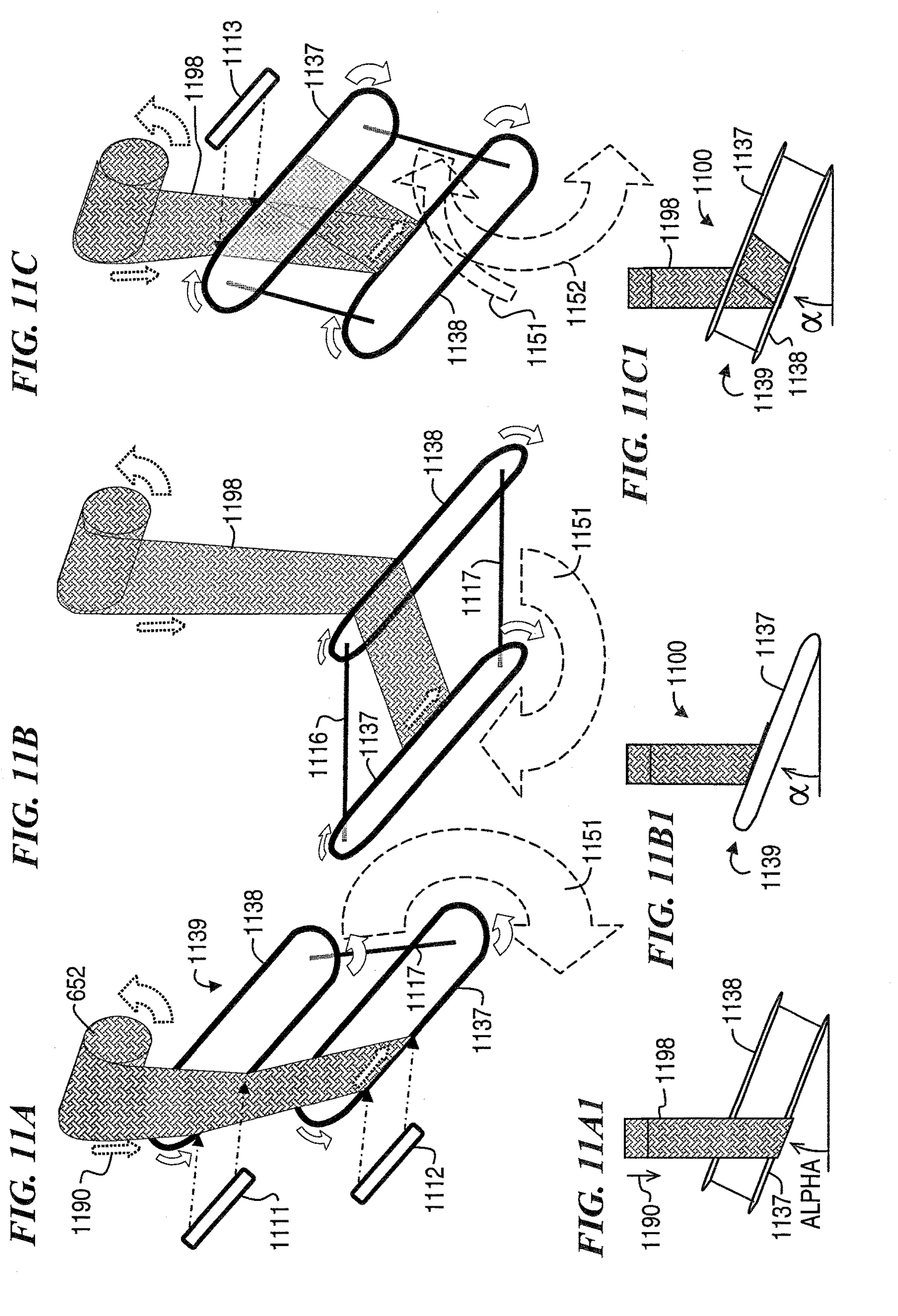


FIG. 11A

FIG. 11A1

FIG. 11B

FIG. 11B1

FIG. 11C

FIG. 11C1

FIG. 11D

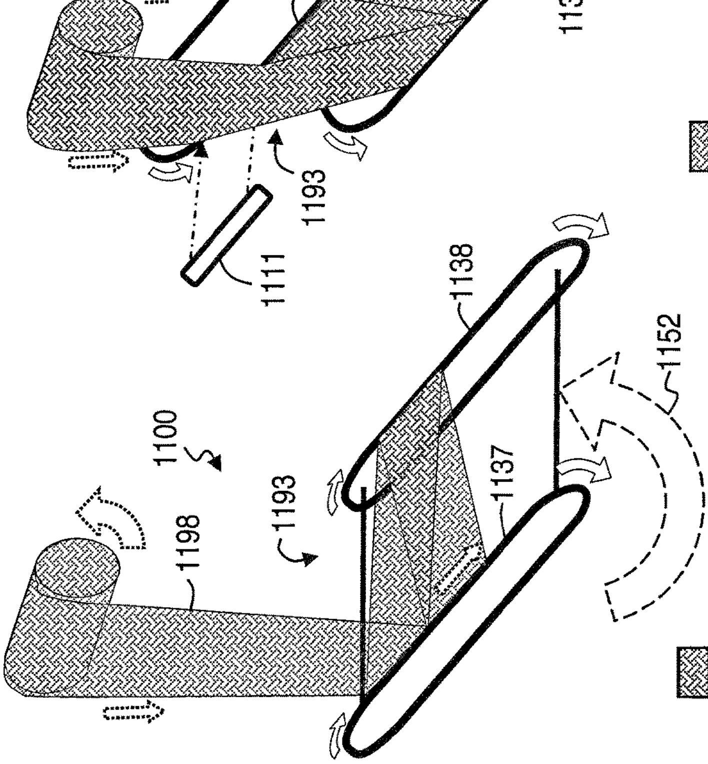


FIG. 11D1

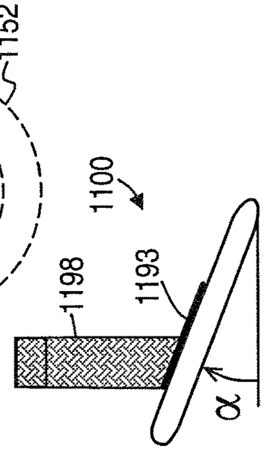


FIG. 11E

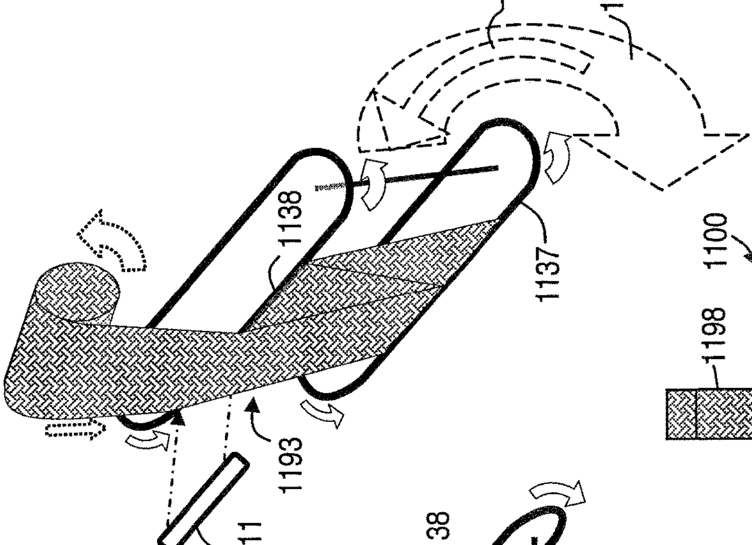


FIG. 11E1

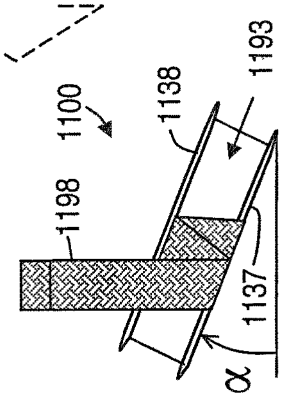


FIG. 11F

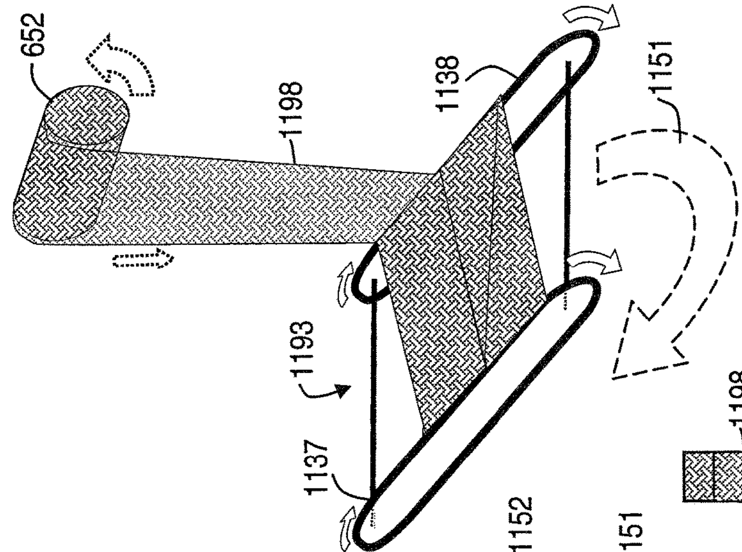
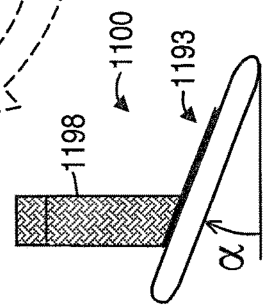


FIG. 11F1



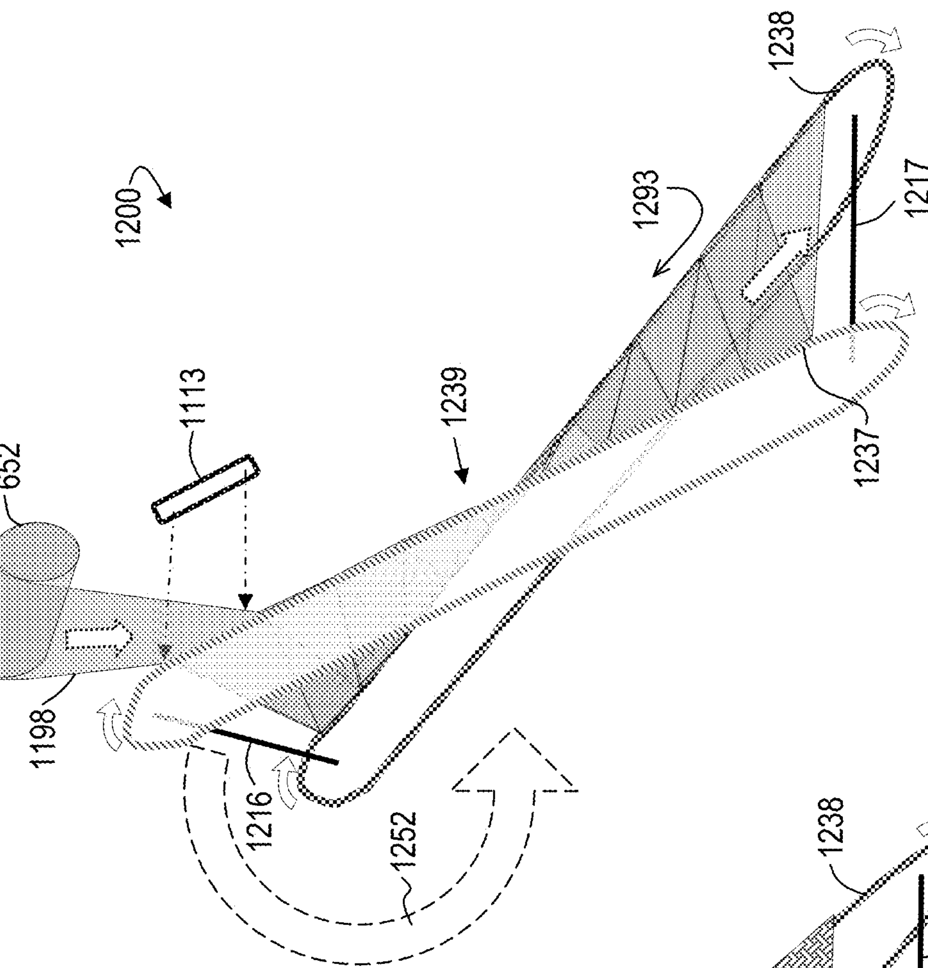


FIG. 12B

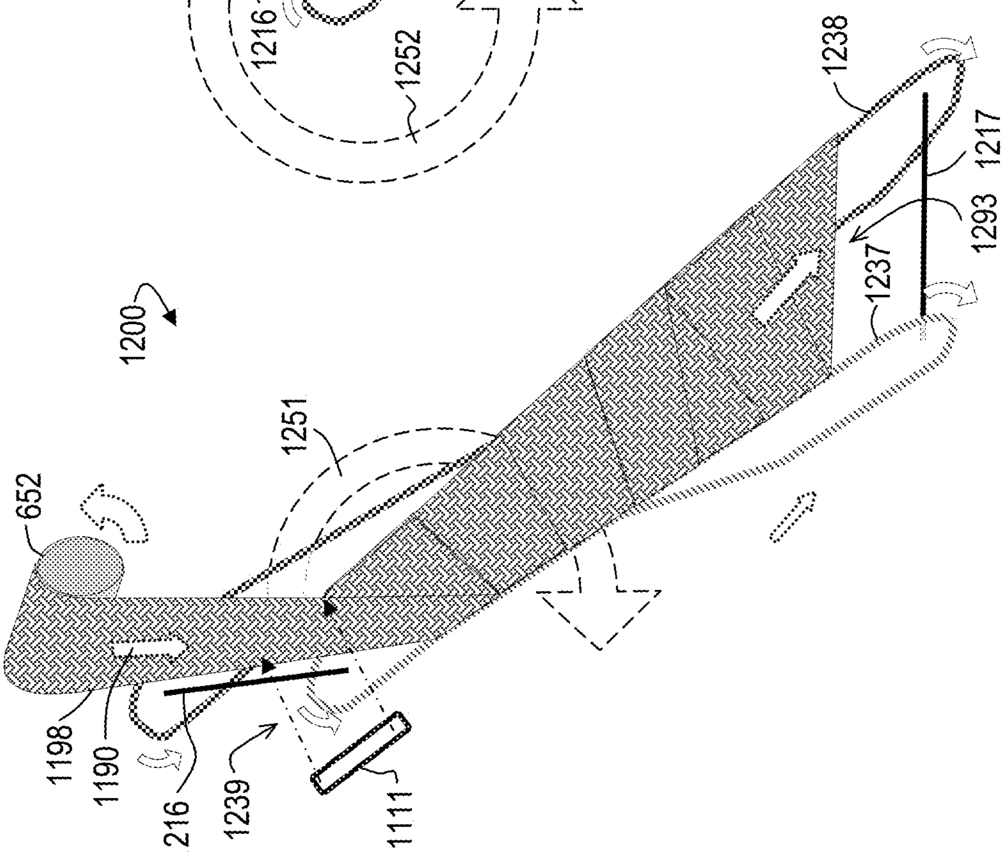


FIG. 12A

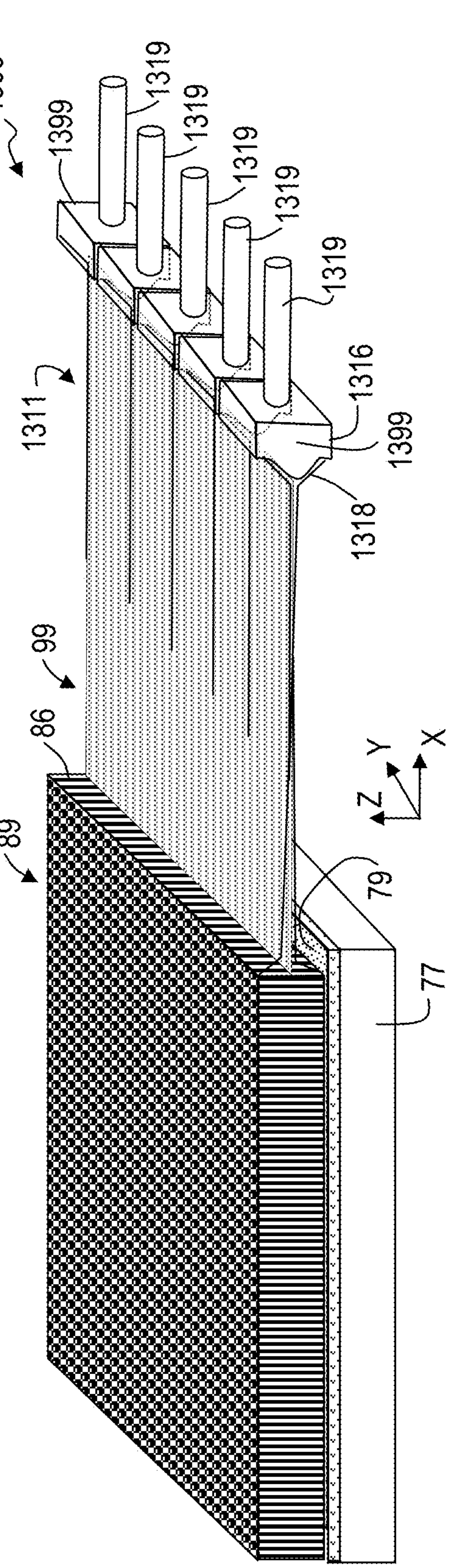


FIG. 13A

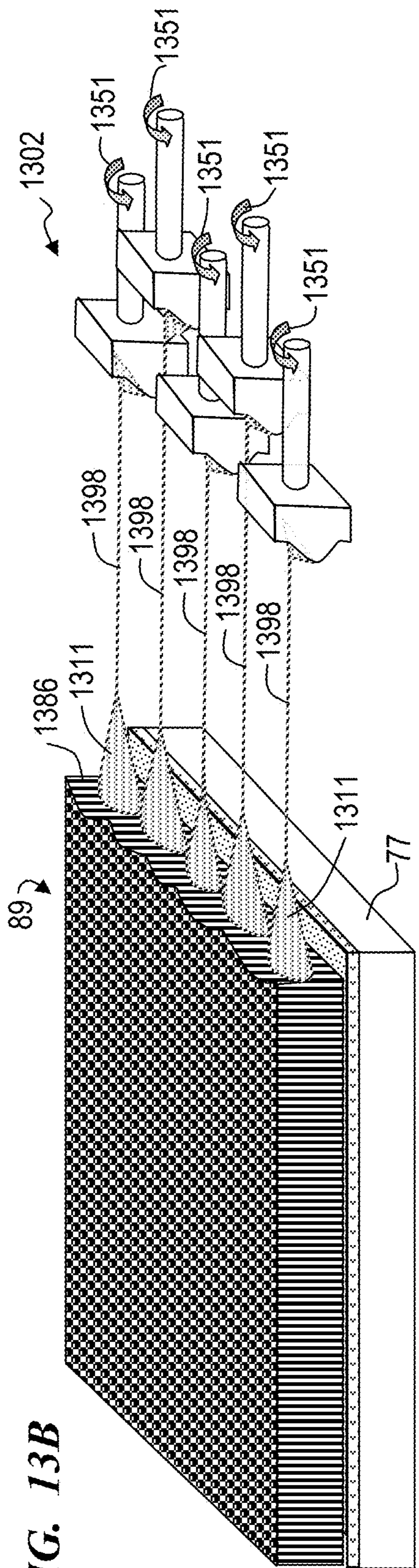


FIG. 13B

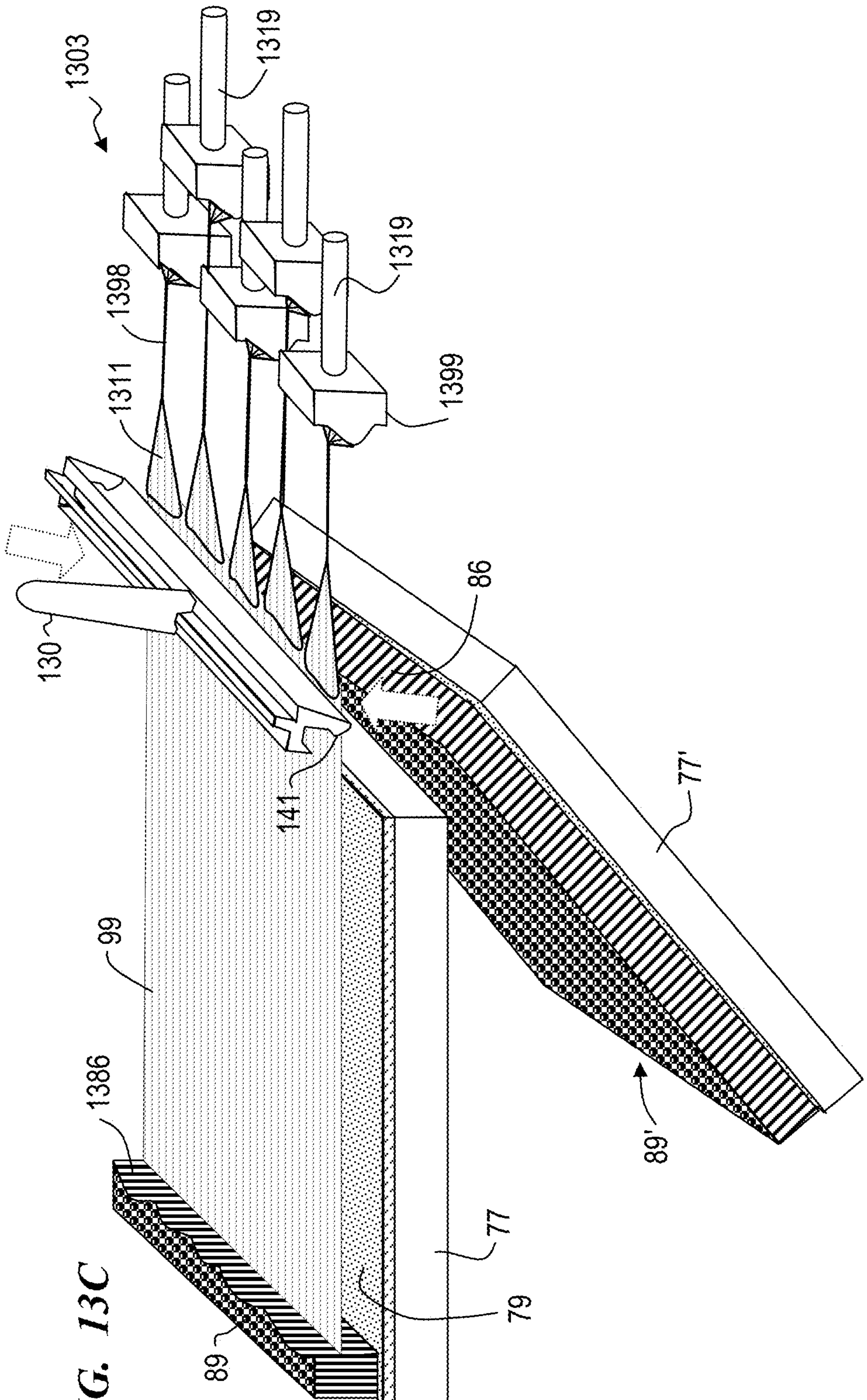


FIG. 13C

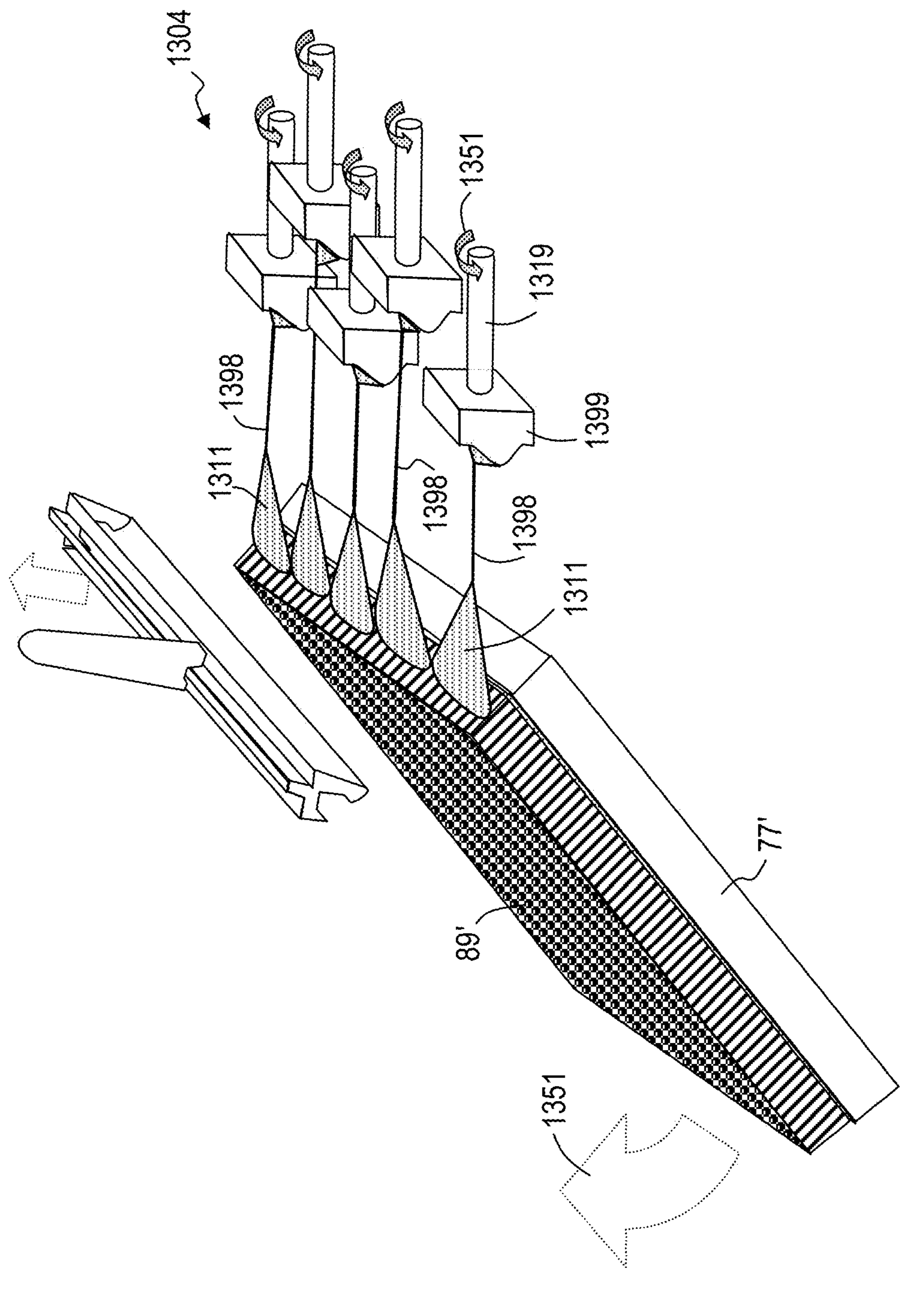


FIG. 13D

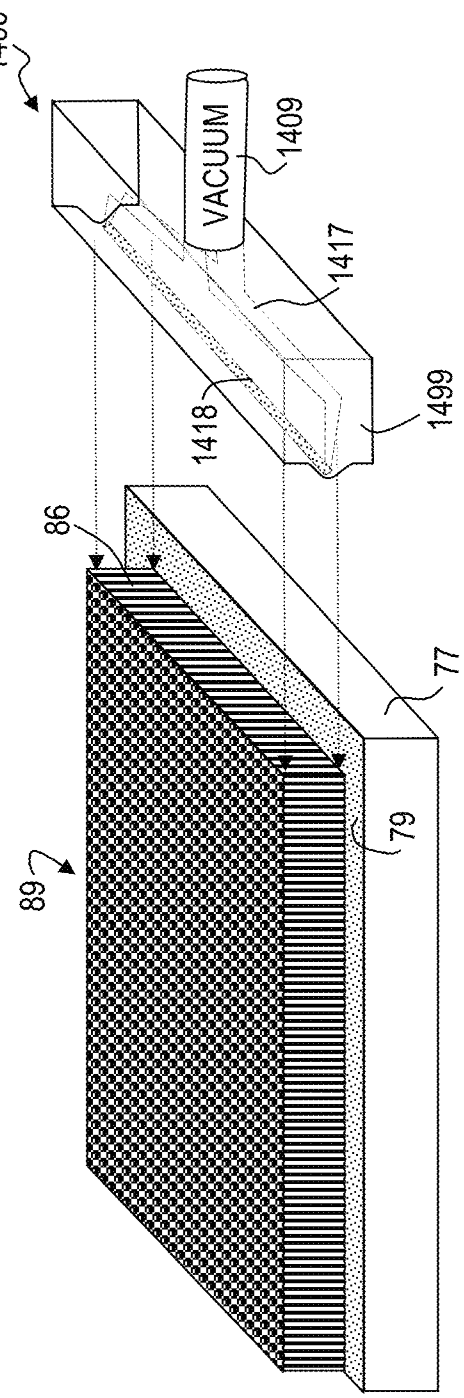


FIG. 14A

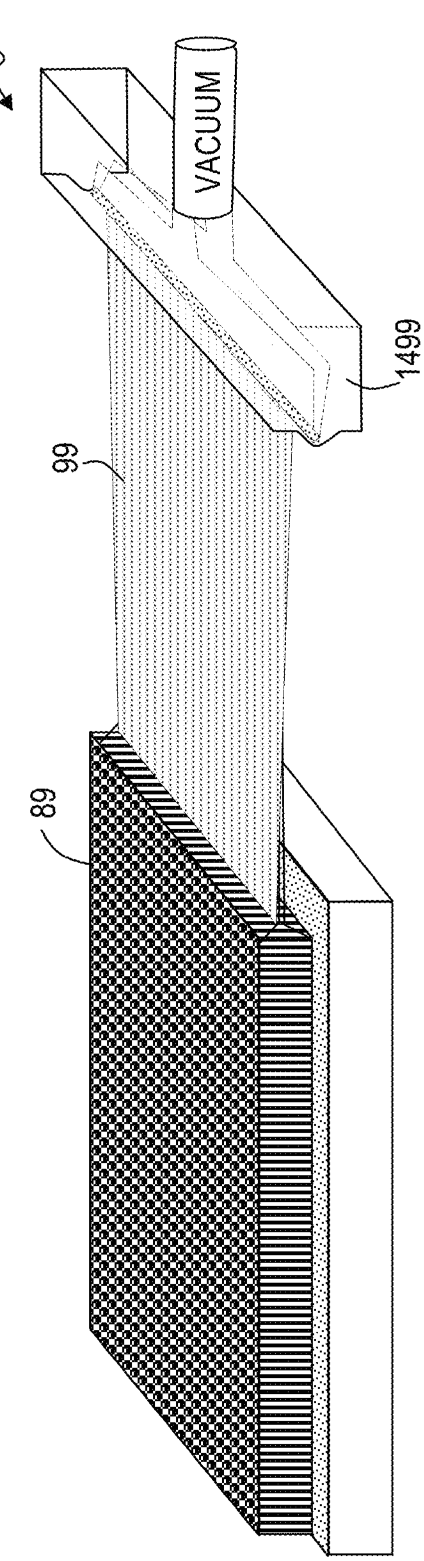


FIG. 14B

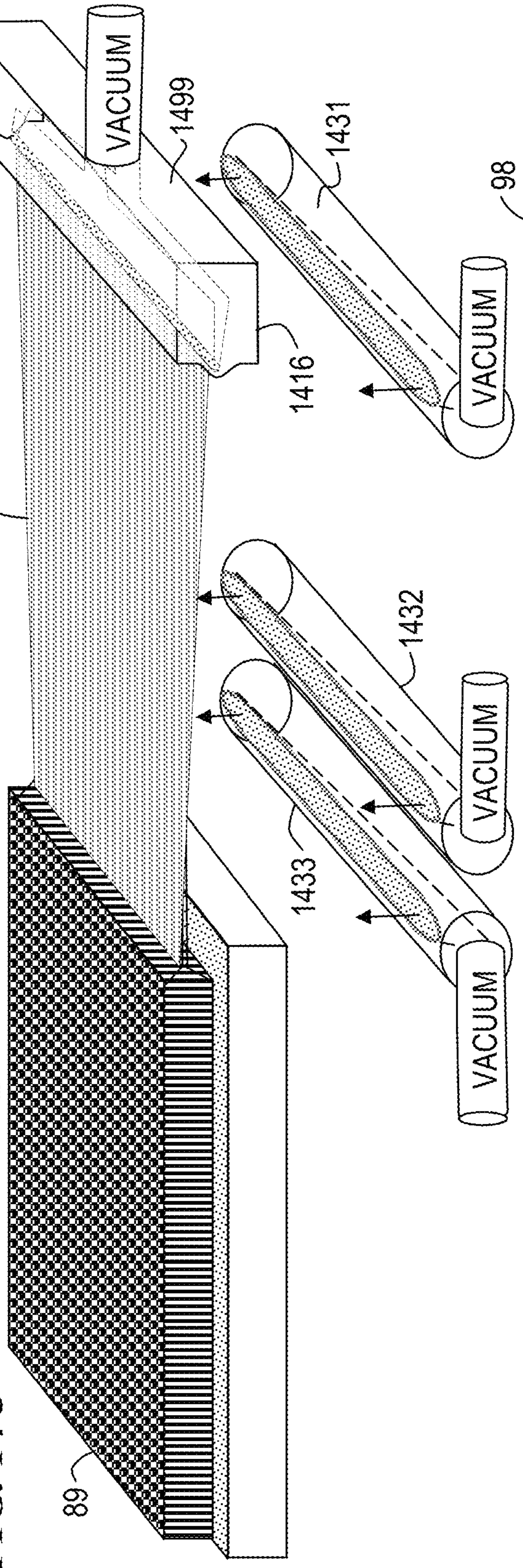


FIG. 14C

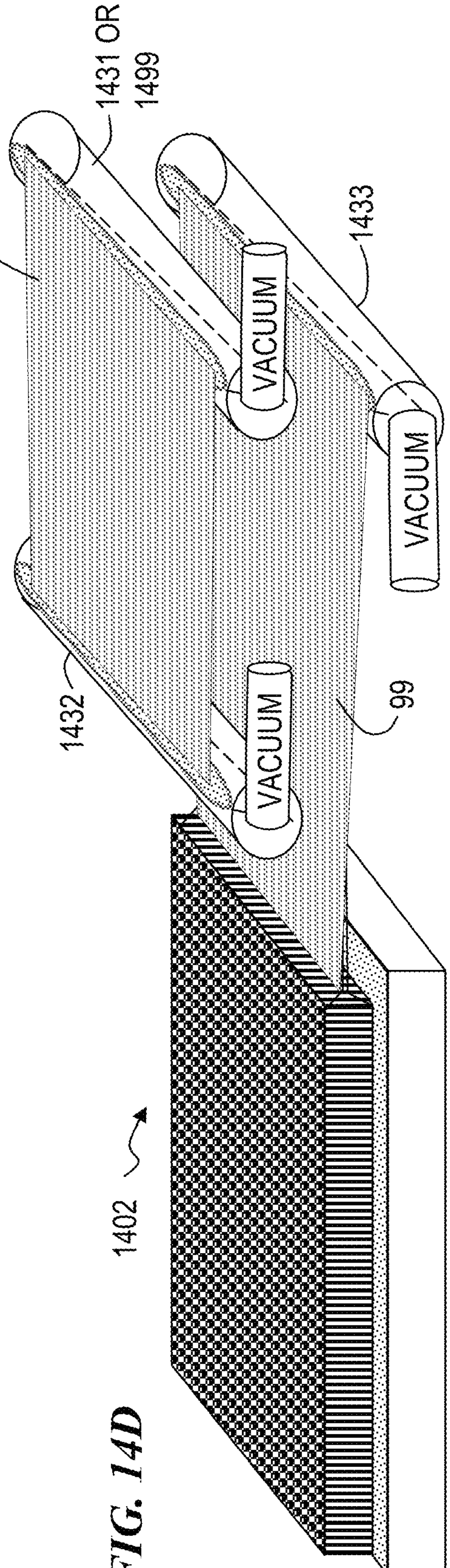


FIG. 14D

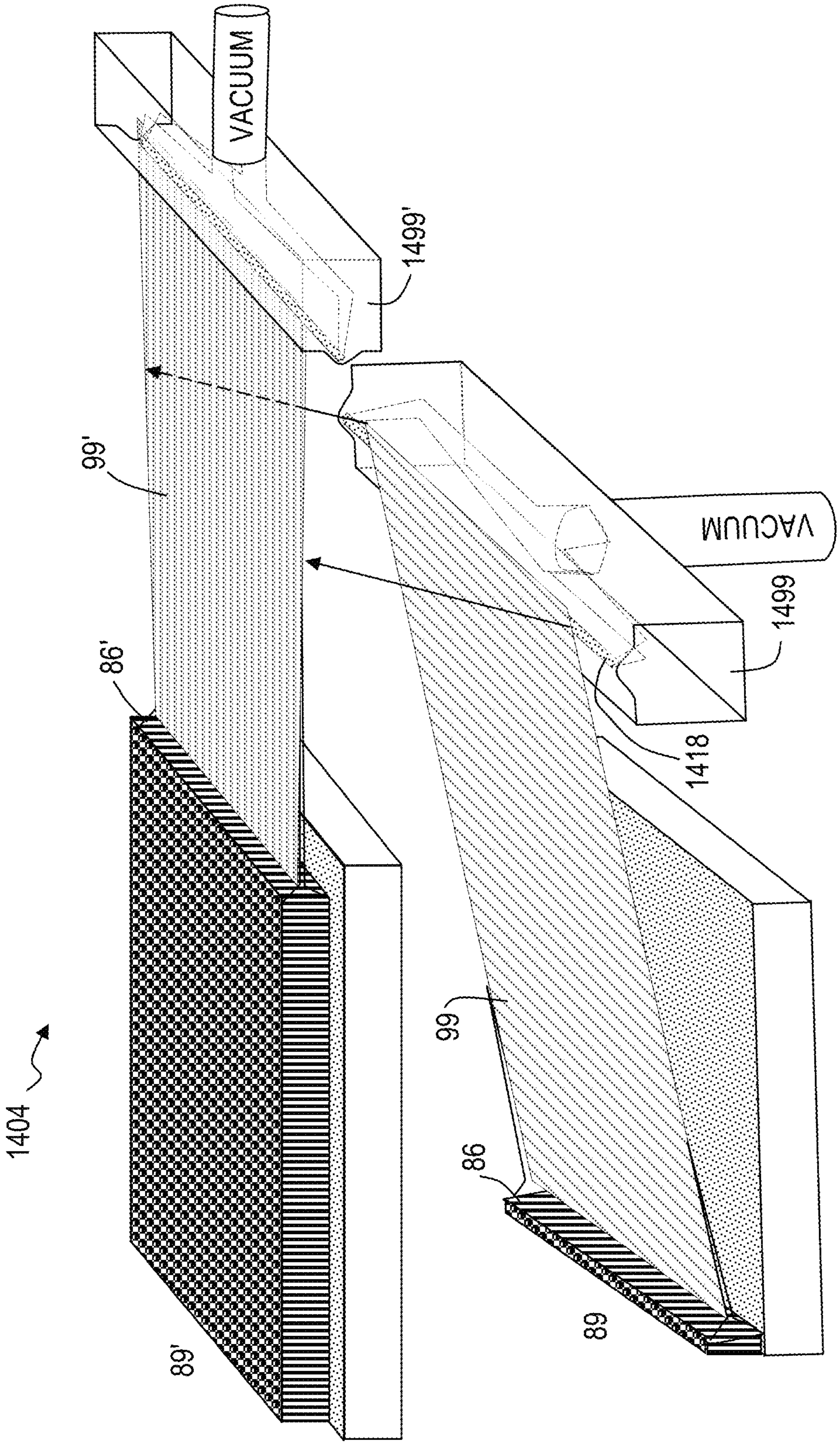


FIG. 14E

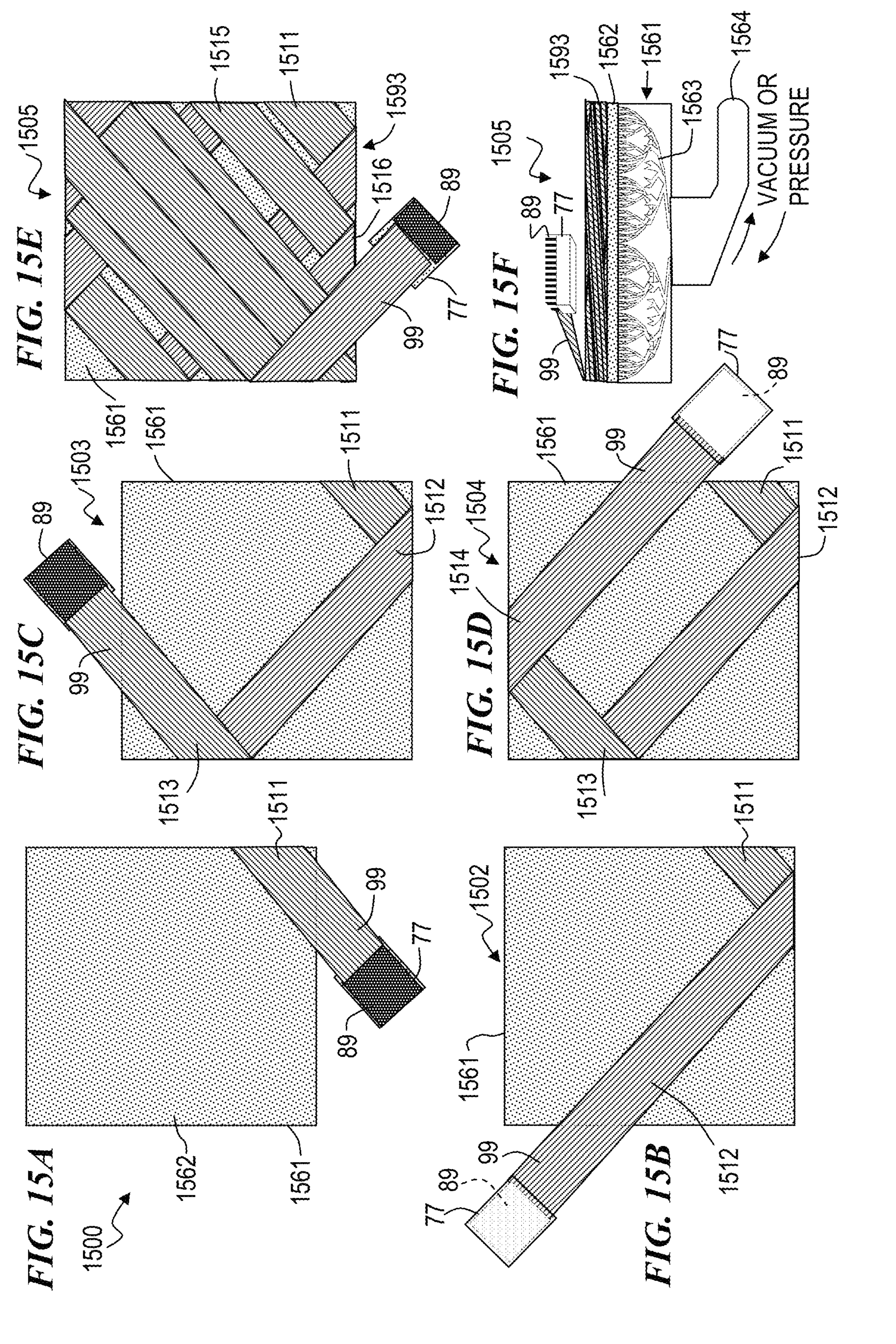


FIG. 15A
FIG. 15B
FIG. 15C
FIG. 15D
FIG. 15E
FIG. 15F

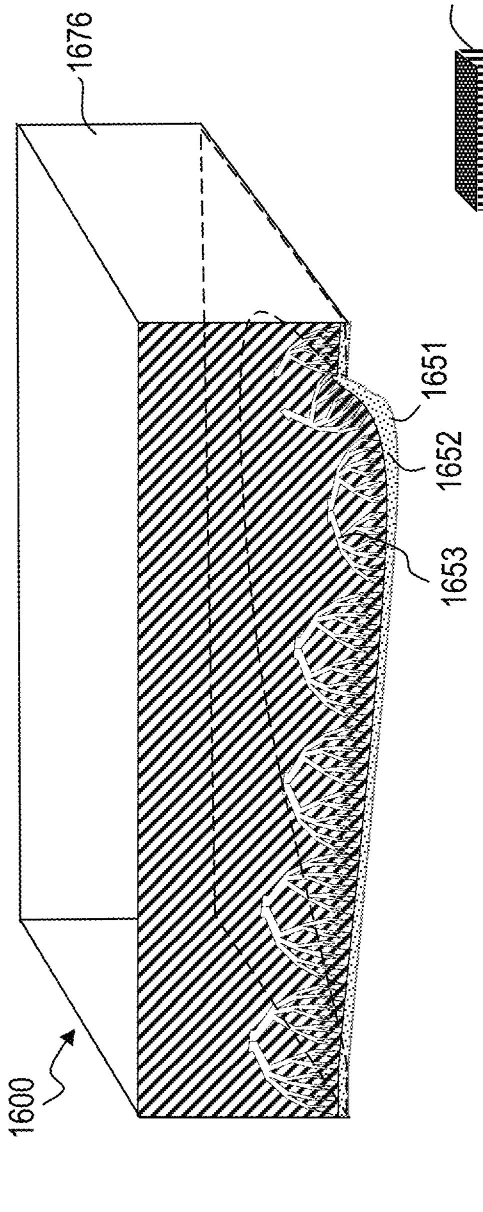


FIG. 16A

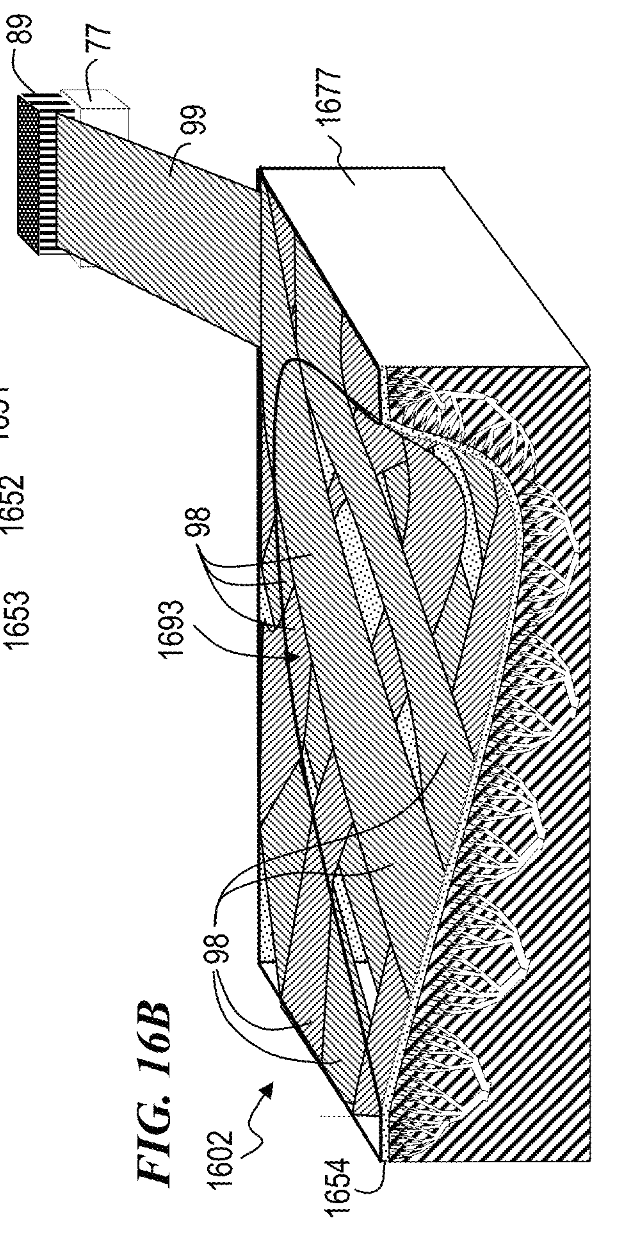


FIG. 16B

APPARATUS FOR GROWING CARBON NANOTUBE FORESTS, AND GENERATING NANOTUBE STRUCTURES THEREFROM, AND METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional application of U.S. patent application Ser. No. 14/049,180, filed Oct. 8, 2013 and titled "APPARATUS FOR GROWING CARBON NANOTUBE FORESTS, AND GENERATING NANOTUBE STRUCTURES THEREFROM, AND METHOD" (which issued as U.S. Pat. No. 8,845,941 on Sep. 30, 2014), which is a divisional application of U.S. patent application Ser. No. 13/454,091, filed Apr. 24, 2012 and titled "METHOD FOR GROWING CARBON NANOTUBE FORESTS, AND GENERATING NANOTUBE STRUCTURES THEREFROM, AND APPARATUS" (which issued as U.S. Pat. No. 8,551,376 on Oct. 8, 2013), which was a divisional application of U.S. patent application Ser. No. 12/794,704, filed Jun. 4, 2010 and titled "METHOD AND APPARATUS FOR GROWING NANOTUBE FORESTS, AND GENERATING NANOTUBE STRUCTURES THEREFROM" (which issued as U.S. Pat. No. 8,162,643 on Apr. 24, 2012), which was a divisional application of U.S. patent application Ser. No. 11/220,455, filed Sep. 6, 2005 and titled "APPARATUS AND METHOD FOR GROWING FULLERENE NANOTUBE FORESTS, AND FORMING NANOTUBE FILMS, THREADS AND COMPOSITE STRUCTURES THEREFROM" (which issued as U.S. Pat. No. 7,744,793 on Jun. 29, 2010), each of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

This invention relates to the field of nanotechnology and specifically to an apparatus and method for generating multi-wall carbon fullerene nanotube "forests," and drawing therefrom sheets, threads, yarns, and/or films using, e.g., various types of adhesion, vacuum holding, surface tension, transport, transfer, weaving, bending, densifying and related techniques.

BACKGROUND OF THE INVENTION

Carbon-based materials, in general, enjoy wide utility due to their unique physical and chemical properties. Recent attention has turned to the use of elongated carbon-based structures, such as carbon fullerene filaments, carbon tubes, and in particular nanosized carbon structures. It has been shown that these new structures impart high strength, low weight, stability, flexibility, good heat and electrical conductance, and a large surface area relative to volume for a variety of applications, such as high-strength fibers, threads, yarns, fabrics, and reinforcement for composites, e.g., nanotube-reinforced epoxy structures.

Of growing commercial interest is the use of single-wall carbon nanotubes to store hydrogen gas, especially for hydrogen-powered fuel cells. Other applications for carbon fibers and/or nanotube materials include catalyst supports, materials for manufacturing devices, such as a tip for scanning electron microscopes, electron field emitters, capacitors, membranes for filtration devices as well as materials for batteries. In short, interest in nanotube technology arises from the very high strength, and electrical and thermo-conductive properties of individual nanotubes.

Finer than carbon fibers, the material with one micron or smaller of diameter is generally called carbon nanotubes and distinguished from the carbon fibers, although no clear line can be run between the both types of carbon fibers. By a narrow definition, the material, of which carbon faces with hexagon meshes are almost parallel to the axis of the tube, is called a carbon nanotube and even a variant of the carbon nanotube, around which amorphous carbon and metal or its catalyst surrounds, is included in the carbon nanotube. (Note that with respect to the present invention, this narrow definition is applied to the carbon nanotube.)

Usually, the narrowly-defined carbon nanotubes are further classified into two types: carbon nanotubes having a structure with a single hexagon-connected carbon-mesh in a tube form are called single-wall nanotubes (hereafter, simply referred to as "SWNT"); the carbon nanotubes made of multi-layer hexagon-connected carbon tubes are called multi-wall nanotubes (hereafter, simply referred to as "MWNT"). When grown from a substantially flat substantially planar surface (e.g., a nanoporous surface coated with an iron-oxide catalyst), the typical result is MWNTs. When grown in a dense aligned structure, the parallel nanotubes somewhat resemble a forest, and are referred to generally as a nanotube forest or more specifically as an MWNT forest. The type of carbon nanotubes may be determined by how they are synthesized and the parameters used to some degree, but production of purely one type of the carbon nanotubes has not yet been achieved.

U.S. Pat. No. 6,232,706 entitled "Self-oriented bundles of carbon nanotubes and method of making same" issued May 15, 2001 to Hongjai Dai et al. is incorporated herein by reference. Dai et al. describe a method of making bundles of aligned carbon nanotubes (e.g., for a field-emission device, such as a plasma TV screen) on a porous surface of a substrate, the method comprising the steps of: a) depositing a catalyst material on the porous surface of the substrate and patterning the catalyst material such that one or more patterned regions are produced; and b) exposing the catalyst material to a carbon-containing gas at an elevated temperature such that one or more bundles of parallel carbon nanotubes grow from the one or more patterned regions in a direction substantially perpendicular to the substrate.

Nanotube forests can be combined together to form structures possessing extreme strength characteristics. These strength characteristics, however, are limited by impurities in the structures themselves arising during the manufacturing process, and/or from the design of the structures such that the maximum possible surface-to-volume ratio is not used by the structure. The present invention addresses these and related issues.

SUMMARY OF THE INVENTION

In some embodiments, the present invention provides improved apparatus and methods for growing nanotube forests (such as carbon fullerene nanotubes arranged in a densely packed aligned configuration synthesized from a catalyst-covered substrate). Some embodiments provide apparatus and methods for making and using improved nanotube-growth substrates. Some embodiments provide apparatus and methods for making and using reaction chambers having access ports for removing nanotubes during the growth cycle on a continuous or repeated basis. Some embodiments provide apparatus and methods for making and using composite structures from the nanotube films.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a perspective schematic diagram of a film-holding-sheet pull initiation using an adhesive sheet to pull a film starting from the top of a carbon-nanotube forest grown on a substrate.

FIG. 1B is a perspective schematic diagram of a film-holding-sheet pull initiation using an adhesive sheet to pull a film starting from the front face of a carbon-nanotube forest.

FIG. 1C is a perspective schematic diagram of a film-holding-bar pull initiation using a cylindrical adhesive-coated bar to initiate a pull at the top and/or front face of a nanotube forest.

FIG. 1D is a perspective schematic diagram of a film-holding-bar pull initiation using an adhesive bar to pull a film starting from the front face of a carbon-nanotube forest.

FIG. 1E is a perspective schematic diagram of a film-holding-sheet pull from the face of a carbon-nanotube forest using an adhesive sheet.

FIG. 1F is a perspective schematic diagram of a film-holding-bar pull from the face of a carbon-nanotube forest using an adhesive bar.

FIG. 1G is a perspective schematic diagram of a film-holding-bar pull from the face of a carbon-nanotube forest using a rounded-front adhesive bar.

FIG. 1H is a perspective schematic diagram of a second adhesive-sheet attachment to the second end of a film already pulled from a face of a carbon-nanotube forest using an adhesive sheet in order to remove the film from the carbon-nanotube forest.

FIG. 1I is a perspective schematic diagram of a carbon nanotube film held at its ends by a first and second adhesive sheet after the film has been removed from the nanotube forest.

FIG. 1J is a perspective schematic diagram of a first, second and third adhesive bar being attached to a film pulled from face of a carbon-nanotube forest using an adhesive bar.

FIG. 1K is a perspective schematic diagram of a carbon nanotube film held at its ends by the first and second adhesive bar after removing the film from the carbon-nanotube forest, while the third adhesive bar is used to pull an additional length of film from a face of the carbon-nanotube forest.

FIG. 1L is a perspective schematic diagram of a stack of carbon nanotube films, each film in the stack being held at its ends by a first and second adhesive sheet, the films stacked one upon another, in order to obtain a plurality of carbon-nanotube films stacked to form a single thicker film structure.

FIG. 1M is a perspective schematic diagram of a flattened or densified stack of carbon nanotube films, the stack held at its ends by the respective stacks of adhesive sheets.

FIG. 1N is a perspective schematic diagram of a flattened or densified stack of carbon nanotube films being removed from the respective stacks of adhesive sheets by other adhesive-sheet members.

FIG. 1-O is a perspective schematic diagram of a flattened or densified stack of carbon nanotube films being held only by the other adhesive-sheet members.

FIG. 1P is a perspective schematic diagram of a flattened or densified stack of carbon nanotube films being removed from the respective stacks of adhesive sheets by other adhesive-bar members.

FIG. 1Q is a perspective schematic diagram of a flattened or densified stack of carbon nanotube films being held only by the other adhesive-bar members.

FIG. 1R is a perspective schematic diagram of a first carbon nanotube film being pulled from a first carbon nanotube forest about to be spliced to a second carbon nanotube forest.

FIG. 1S is a perspective schematic diagram of a first carbon nanotube film being pulled from a first carbon nanotube forest being spliced to a second carbon nanotube forest.

FIG. 1T is a perspective schematic diagram of a first carbon nanotube film being pulled from the second carbon nanotube forest after being spliced and removed from the first carbon nanotube forest.

FIG. 1U is a perspective schematic diagram of a first carbon nanotube film being pulled from a first carbon nanotube forest on the top of a first double-sided substrate about to be spliced to a second carbon nanotube forest on the top of a second double-sided substrate.

FIG. 1V is a perspective view of a film-holder opener for a clamping holder.

FIG. 1W is a top view of the film-holder opener.

FIG. 1X is an end view of the film-holder opener.

FIG. 1Y is a side view of the film-holder opener.

FIG. 1Z is a perspective schematic diagram of a carbon nanotube film being inserted into a clamping film-holding-bar such as a split rubber tube.

FIG. 2A is a perspective schematic diagram of an assembly of carbon nanotube films, each film in the assembly being held at its ends by a first and second adhesive rod, band or other or member, the films placed one next to another and each transferred from its respective transportation holder, in order to obtain a plurality of carbon-nanotube films placed to form a single wider and/or woven film structure.

FIG. 2B is a perspective schematic diagram of an assembly of carbon nanotube films, each film in a first direction being held at its ends by a first and second adhesive member, the films placed one next to another and each transferred from its respective transportation holder, each film in a second direction being held at its ends by a third and fourth adhesive member, the films placed one next to another and each transferred from its respective transportation holder, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films.

FIG. 2C is a perspective schematic diagram of a loom that provides a woven assembly of carbon nanotube films, each film in the assembly being held at its ends by a first and second adhesive rod, band or other or member.

FIG. 2D is a perspective schematic diagram of an assembly of carbon nanotube films, each film in a first direction being held at its ends by a first and second adhesive member, each film in a second direction being held at its ends by the first and second member, the films placed one next to another and each transferred from its respective transportation holder, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web.

FIG. 2E is a perspective schematic diagram of loom that provides a woven assembly of carbon nanotube films, each film in the assembly being held at its ends by a first and second adhesive member, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web.

FIG. 2F is an end-view schematic diagram of the continuous-loop loom.

FIG. 3A is a perspective schematic diagram of a carbon nanotube film being pulled from a carbon nanotube forest having a gap in the nanotube forest.

FIG. 3B is a perspective schematic diagram of a carbon nanotube film being pulled from a carbon nanotube forest having a gap in the nanotube forest in a manner that suppresses any gap in the film.

FIG. 4A is a perspective cross-section schematic diagram of an apparatus for the continuous synthesis and collection of carbon nanotubes.

FIG. 4B is a cross-section side view of an apparatus for the continuous synthesis and collection of carbon nanotubes.

FIG. 4C is a top-view of an apparatus for the continuous synthesis and collection of carbon nanotubes.

FIG. 5A is a perspective schematic diagram of an apparatus for the continuous synthesis and collection of carbon nanotubes during an intermediate collection stage of one round of synthesis.

FIG. 5B is a cross-section side view of an apparatus for the continuous synthesis and collection of carbon nanotubes during an intermediate collection stage of one round of synthesis.

FIG. 5C is a cross-section side view of an apparatus for the continuous synthesis and collection of carbon nanotubes at a later collection stage of one round of synthesis.

FIG. 5D is a cross-section side view of an apparatus for the continuous synthesis and collection of carbon nanotubes at a cutting and reattachment collection stage of one round of synthesis.

FIG. 5E is a cross-section side view of an apparatus for the continuous synthesis and collection of carbon nanotubes following reattachment to initiate a fresh collection stage.

FIG. 5F is a cross-section side view of an apparatus for the synthesis of carbon nanotubes using a double-sided flow-through substrate.

FIG. 5G is a cross-section side view of a system for growing densely packed carbon nanotube forests continuously to very long lengths.

FIG. 5H is a cross-section side view schematic of a carbon-nanotube-synthesis apparatus having a heat trap.

FIG. 6A is a cross-section side view of an apparatus that includes flow-through linked substrates for the continuous synthesis of carbon nanotubes.

FIG. 6B is a close-up side view of flow-through linked substrates used for the continuous synthesis of carbon nanotubes that illustrates the continuous collection of carbon nanotubes from the flow-through linked substrates.

FIG. 6C is a cross-section side view of an apparatus for the continuous synthesis of carbon nanotubes in which the nanotubes are continuously collected in a downward manner.

FIG. 6D is a cross-section side view of an over/under furnace and cool-box apparatus.

FIG. 7A is a cross-section side view of an apparatus for the continuous synthesis of carbon nanotubes in which the nanotubes are continuously collected from a substantially cylindrical flow-through substrate.

FIG. 7B is a side-view of an apparatus for the continuous synthesis of carbon nanotubes in which the nanotubes are continuously collected from a substantially cylindrical flow-through substrate.

FIGS. 8A-8K are perspective schematic diagrams of steps in making a flow-through substrate for growing carbon nanotube forests.

FIG. 8L is a bottom-view schematic diagram of a flow-through substrate for growing a carbon nanotube forest.

FIG. 8L1 is a close-up bottom-view schematic diagram of a flow-through substrate for growing a carbon nanotube forest.

FIGS. 8M-8P are perspective schematic diagrams of alternative steps in making a flow-through substrate for growing carbon nanotube forests.

FIGS. 9A, 9B, 9C, 9D, 9E, 9F, and 9G are perspective schematic diagrams of steps in making a substrate **977** into a flow-through substrate **905** for growing carbon nanotube forests.

FIG. 9H is a perspective-view schematic diagram of a partially processed substrate **906** that results after substrate **978** (e.g., made of a silicon wafer having a 100-crystal orientation at its top surface) has been deep etched to create grooves or channels **919** by deep reactive ion etching (DRIE), as described for FIG. 9A.

FIG. 9I is a perspective-view schematic diagram of a partially processed substrate **907** after substrate **978** has been processed to fill channels **919** and channels **920** with SiO_2 to form silicon dioxide strips **918** and **929**, which support the epitaxial lateral overgrowth (ELOG) of silicon top layer **921**, but will then later be etched away to leave lateral gas passages having at least one gas inlet port through a side wall **960** of substrate **978**.

FIG. 9J is a perspective-view schematic diagram of a mostly processed substrate **908** after substrate **978** has been processed with a nanoporous etch as described above for FIG. 8G.

FIGS. 9K and 9L are perspective schematic diagrams of steps in making a substrate **977** into a side-flow or through-flow dugout substrate **982** for growing carbon nanotube forests.

FIGS. 9M, 9N, and 9O are perspective schematic diagrams of steps in making a substrate **977** into a side-flow or through-flow substrate **985** for growing carbon nanotube forests.

FIGS. 10A, 10B, 10C, and 10D are schematic perspective-view, cross-section view, close-up perspective view and top view diagrams, respectively, of making a continuous-web carbon nanotube film structure.

FIG. 10E is a perspective schematic diagram of densification steps in making a densified continuous-web carbon nanotube film structure.

FIGS. 11A, 11B, 11C, 11D, 11E, and 11F are perspective-view schematic diagrams of system **1100** making a continuous web of crossed films, where each film in the assembly is being held at its ends by a first and second adhesive member of a conveying mechanism, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web.

FIGS. 11A1, 11B1, 11C1, 11D1, 11E1, and 11F1 are side-view diagrams of system **1100** as shown in FIGS. 11A-11F.

FIGS. 12A and 12B are perspective-view schematic diagrams of making a continuous web of crossed films, where each film in the assembly is being held at its ends by a first and second adhesive member of a conveying mechanism, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web.

FIGS. 13A and 13B are perspective schematic diagrams of making a plurality of continuous yarns from a plurality of carbon-nanotube films pulled from carbon-nanotube forests.

FIGS. 13C and 13D are perspective-view schematic diagrams of splicing films and/or yarns while making a plurality of continuous yarns from a plurality of carbon-nanotube forests on different substrates.

FIGS. 14A and 14B are perspective-view schematic diagrams of initiating and pulling a continuous film from a carbon-nanotube forest using vacuum film-holding bars.

FIGS. **14**C and **14**D are perspective schematic diagrams of transferring films pulling a continuous film from a carbon-nanotube forest using vacuum film-holding bars.

FIG. **14**E is a perspective schematic diagram of splicing films while pulling a continuous film from carbon-nanotube forests on different substrates using vacuum film-holding bars.

FIGS. **15**A, **15**B, **15**C, **15**D, **15**E, and **15**F are top-view schematic diagrams of system **1500** building a cross-woven nanotube cloth on a vacuum table.

FIGS. **16**A and **16**B are perspective schematic diagrams of system **1600** building a cross-woven nanotube airfoil using a continuous web of crossed films, where each film in the assembly is being held across its entire length and width by a curved vacuum table.

DESCRIPTION OF EMBODIMENTS

In the following detailed description of the preferred embodiments, reference is made to the accompanying drawings that form a part hereof, and in which are shown by way of illustration specific embodiments in which the invention may be practiced. It is understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

The leading digit(s) of reference numbers appearing in the Figures generally corresponds to the Figure number in which that component is first introduced, such that the same reference number is used throughout to refer to an identical component which appears in multiple Figures. Signals and connections may be referred to by the same reference number or label, and the actual meaning will be clear from its use in the context of the description.

The Formation of Nanotube Fibers

The generation of carbon nanotube fibers is an aspect of some embodiments of the present invention and can be achieved using known techniques, such as those described in U.S. Pat. No. 6,232,706 (the Dai et al. Patent), incorporated by reference herein in its entirety. The Dai et al. U.S. Pat. No. 6,232,706 discloses a method of making carbon nanotube bundles attached to substrates.

Some embodiments apply a modification of a method disclosed in U.S. Pat. No. 6,232,706 in order to make large areas of aligned and closely packed carbon nanotubes across substantially the entire top surface of a solid silicon substrate: in a first step A, in some embodiments, a highly P-doped n^+ type silicon substrate (100-oriented-crystal top surface, resistivity 0.008-0.018 Ohm-cm) is electrochemically etched in 1:1 HF (49% in water) ethanol with an anodization current density of 10 mA/cm^2 (typical etching time is 5 minutes). This forms a thin nanoporous layer (pore size about 3 nanometers) on top of a microporous layer (pore size about 100 nanometers). Next, in a step B, in some embodiments, the top of the porous layer is covered substantially in its entirety (unlike Dai et al.) with a five-nanometer thick iron (Fe) film by e-beam evaporation. In some embodiments, after deposition of iron, the substrate is annealed in air at 300 degrees C. overnight. This annealing step oxidizes the surface of the silicon as well as the iron, converting the iron patterns into catalytically active iron-oxide. The resulting silicon dioxide layer formed on the underlying porous silicon prevents the porous structure of layers from collapsing during the following high-temperature chemical vapor deposition (CVD) step.

Next, in a step C, in some embodiments, the substrate is placed in a tube reactor housed in a tube furnace. The furnace is preheated to 700 degrees C. (or 680 degrees C.) in a flowing inert gas such as argon (or helium). Then, at 700 degrees C. (or 680 degrees C.), the argon (or helium) supply is turned off, and ethylene is flown through the tube reactor at a rate of 1000 sccm/min for 15-60 minutes, (or a mixture of 5 mol % acetylene in a Helium carrier is flown through the tube reactor at a rate of 850 sccm/min for about 10 minutes). The boat for the substrate(s) is sealed at one end, and the sealed end is placed downstream in the furnace. While ethylene is flowing, the iron-oxide surface catalyzes the growth of carbon nanotubes, which grow perpendicular to the substrate. In some embodiments, the iron film is patterned (e.g., by deposition through a shadow mask). If the iron is patterned (e.g., into islands or strips), the width of the bundles is the same as the width of the iron-oxide patterns. Accordingly, the width of the bundles can be tailored to a specific width depending upon the iron oxide patterns used in forming the bundles.

Other embodiments use methods to generate carbon nanotube fibers such as those described in an article by Zhang, Atkinson & Baughman titled "Multifunctional Carbon Nanotube Yarns by Downsizing an Ancient Technology," *Science*; Vol. 306 Nov. 19, 2004 at 1358-1361 (the Zhang et al. 2004 article, which is incorporated herein by reference). Zhang et al. 2004 give credit to, and build on, important advances of the Dai group (S. Fan et al., "Self-Oriented Regular Arrays of Carbon Nanotubes and Their Field Emission Properties," *Science* 283, 512 (1999)) and the Ren group (Z. F. Ren et al., *Synthesis of Large Arrays of Well-Aligned Carbon Nanotubes on Glass*, Science 282, 1105 (1998)). Zhang et al. 2004 disclose a method of manufacturing an aligned nanotube forest, whereby MWNTs (for example) are synthesized in a quartz tube 45 mm in diameter by atmospheric-pressure CVD of 5 mol % C_2H_2 in He at 680 degrees C., at a flow rate of 580 sccm for 10 minutes. In some embodiments, the nanotube forest is grown on an iron (Fe) film, 5 nm thick, which, in turn, is deposited on a silicon (Si) wafer substrate by electron beam evaporator. Using this method, various yarns composed of carbon nanotube fibers were generated by Zhang et al. 2004, with a purity of between 96 to 98% and 2 to 4% Fe and amorphous carbon.

Additionally discussed in Zhang et al. 2004 is a method by which various yarns are generated using the fibers created from a MWNT forest, wherein these fibers are twisted together to approximately 80,000 turns/meter such that once the ends of the twisted fibers are released the twisted structure is retained. According to Zhang et al. 2004, this twisted structure is retained, in part, because of the very high surface-to-volume ratio between the MWNTs.

The generation of carbon nanotube forests is a component of some embodiments of the present invention and can be achieved either using the new techniques described herein, or by known techniques, such as those described in an article titled "Strong, Transparent, Multifunctional, Carbon Nanotube Sheet," *Science*, Vol. 309 Aug. 19, 2005 at 1215-1219 (the Zhang et al. 2005 article, which is incorporated herein by reference).

Zhang et al. 2005 mention a method of manufacturing a MWNT forest based upon the techniques as described above by Zhang et al. 2004 and apply these techniques to the manufacture of MWNT sheets. In manufacturing such sheets, a MWNT forest is generated applying the techniques of Zhang et al. 2004. The techniques of Dai et al. could also be applied to generate such forests. Zhang et al. 2005 draw

MWNT sheets from the MWNT forest using an adhesive strip (e.g., a 3M Post-It Note™) to contact the MWNTs and draw a sheet therefrom. In some embodiments, a 1-cm length of 245-micron-high (i.e., about 0.25 mm) forest converts to about a 3-m long (a 300:1 ratio) strip of freestanding MWNT sheet. Once drawn, these sheets can be stacked one on top of another for increased strength, set in an overlay or crossed-film pattern.

Moreover, Zhang et al. 2005 describe a process of densifying these MWNT sheets whereby the sheets are placed/attached onto a planar substrate composed of glass, gold, silicon, aluminum, steel, plastic or some other substrate known in the art. The process includes immersing the substrate and attached MWNT sheet vertically into a bath of a liquid, such as ethanol, and then retracting the substrate vertically from the liquid and drying. The thinning and surface tension of the liquid evaporating shrinks the thickness of the MWNT sheet, thus making the carbon nanotube sheets themselves denser. Some embodiments of the invention use improved methods for applying and evaporating a densifying liquid on a continuous basis to a web moving in a continuous or roll-to-roll manner.

Some embodiments of the present invention use improved MWNT-forest-growing techniques to make carbon nanotubes, the methods modified from those described in the above-mentioned published articles and U.S. Pat. No. 6,232,706. Other embodiments of the present invention use improvements of methods such as described in U.S. Patent Application US 2004/0062708A1 published Apr. 1, 2004 by Remskar et al, in order to make nanotubes from materials other than carbon, for example synthesis and self-assembly of single-wall subnanometer-diameter molybdenum disulfide tubes. In some embodiments, the nanotubes contain interstitial iodine, which is removed as the molybdenum-disulfide-nanotube forest is pulled into molybdenum-disulphide nanotube films. In some embodiments, synthesis is performed using a catalyzed transport reaction similar to that described by Remskar including C60 as a growth promoter. In contrast to Remskar et al., the present invention, in some embodiments, uses modifications and new techniques similar to those described below, but using a quartz substrate for the molybdenum-disulfide-nanotube growth surface.

FIG. **1**A is a perspective schematic diagram of system **100** in which a film-holding-sheet pull initiation uses an adhesive sheet **110** (such as a Post-It®-brand sticky note, Scotch®-brand transparent sticky tape or other suitable substrate having an adhesive area **112**) from the top **87** of a carbon-nanotube forest **89** grown on a substrate **77**. In some embodiments, substrate **77** has a nanoporous top surface **79** having a catalyst (such as iron oxide, for example—in some embodiments, a 5-nm iron film is oxidized to form the catalyst; in other embodiments, one or more other transition metals are substituted for, or added to, the iron, such as nickel, cobalt, or other suitable composition) suitable for growing tubular fullerene structures (e.g., multi-walled carbon nanotubes, or MWNTs). In some embodiments, nanotube forest **89** includes a large plurality of substantially aligned, densely packed MWNTs. In other embodiments, forest **89** includes a large plurality of substantially aligned, densely packed single-walled nanotubes, or SWNTs. In other embodiments, nanotubes made of other materials such as Forest **89** includes a nanotube forest front wall **86** that exposes the left-hand sides (relative to the drawing) of an outer row of nanotubes and from which a film will be drawn, nanotube forest base **85** where the nanotubes are connected to the catalyst surface of substrate **77** (where it is believed that growth takes place), nanotube forest top **87**, nanotube forest back wall **88**, and nanotube forest side walls **84**. In some embodiments, a nanotube film **99** is started by pressing adhesive sheet **110** onto forest top **87** where it meets forest front **86**, and then pulling adhesive sheet **110** towards the right. Other embodiments substitute a film-holding sheet **110** having a liquid such as alcohol, water, and/or oil to hold nanotube film **99** in place, rather than (or in addition to) adhesive **112** (this optionally applies to all embodiments described herein).

FIG. **1**B is a perspective schematic diagram of system **100** in which a film-holding-sheet pull initiation uses an adhesive sheet **110** where adhesive area **112** is initially pressed against front face **86** of carbon-nanotube forest **89**, and then adhesive sheet **110** is withdrawn towards the right.

FIG. **1**C is a perspective schematic diagram of system **100** in which a film-holding-bar pull initiation uses an adhesive bar **114** having an adhesive surface **116** from the top **87** and/or front face **86** of carbon-nanotube forest **89**. In some embodiments, adhesive surface **116** (and/or the other adhesive surfaces described herein) includes an adhesive such as found on a Post-It®-brand sticky note, Scotch®-brand transparent sticky tape, such as described in U.S. Pat. No. 6,479,073 entitled "Pressure sensitive adhesive articles and methods for preparing same" or U.S. Pat. No. RE24,906 entitled "Pressure-sensitive adhesive sheet material" by inventor Erwin W. Ulrich (both of which patents are incorporated herein by reference) or other suitable adhesive.

Other embodiments substitute a film-holding bar **114** (and/or similar structures for the other adhesive surfaces described herein) having a liquid such as ethanol or other alcohol (such as poly (vinyl alcohol)), water, and/or oil selected for its ability to hold nanotube film **99** in place, rather than (or in addition to) adhesive **116** (this optionally applies to all embodiments described herein). Still other embodiments substitute a vacuum film-holding bar **1410**, as described below in FIG. **14**E, to hold nanotube film **99** in place, rather than (or in addition to) adhesive **116** (this optionally applies to all embodiments described herein).

FIG. **1**D is a perspective schematic diagram of system **100** in which a film-holding-bar pull initiation uses an adhesive bar **118** having an adhesive surface **119** from front face **86** of carbon-nanotube forest **89**. In some embodiments, bar **118** has a bottom surface **116** that rests on substrate surface **79** as the adhesive-coated rounded front nose **117** of bar **118** is moved into engagement with forest front face **86**, wherein the spacing between bottom **116** and nose **117** is selected such that nose **117** first contacts approximately the midpoints of nanotubes **80**. In other embodiments, the spacing between bottom **116** and nose **117** is selected such that nose **117** first contacts below the midpoints of nanotubes **80**, and bar **118** is first moved upward slightly while adhesive **119** is in contact with the front face **86** and then bar **118** is pulled to the right or in a general direction to the right relative to the orientation in FIG. **1**D.

FIG. **1**E is a perspective schematic diagram of a film-holding-sheet pull or draw from the face **86** of a carbon-nanotube forest **89** using an adhesive sheet **110**.

FIG. **1**F is a perspective schematic diagram of a film-holding-bar pull from the face **86** of a carbon-nanotube forest **89** using an adhesive bar **113** having an adhesive face **112**.

FIG. **1**G is a perspective schematic diagram of a film-holding-bar pull from the face **86** of a carbon-nanotube forest **89** using a rounded-front adhesive bar **118**. Generically, all of the film-holding bars (including the vacuum bars of FIG. **14**) herein can be used for pulling or holding film **99**, and are referred to simply as film-holding puller bar **199** when being used to pull a carbon nanotube film **99** from a forest **89**.

FIG. **1**H is a perspective schematic diagram showing attachment of a second adhesive sheet **111** to the second end of a film **99** pulled to a desired length from a face of a carbon-nanotube forest **89** using an adhesive sheet **110**. In some embodiments, a third adhesive sheet is simultaneously attached to the bottom of film **99** at a location closer to forest **89**, and the film **99** is cut, torn, or otherwise separated between the second adhesive sheet **111** and the third adhesive sheet, which then becomes adhesive sheet **110** for the continued pulling of additional film **99** from forest **89**, while the removed film **98** is held by first and second adhesive sheets **110** and **111**.

FIG. **1**I is a perspective schematic diagram of a carbon nanotube film **98** held at its ends by first adhesive sheet **110** and second adhesive sheet **111**, after the film **98** has been pulled and then removed from the carbon-nanotube forest **89**. In some embodiments, a spacer bar **121** is used to hold one or more first adhesive sheets **110** and second adhesive sheets **111** at a fixed distance apart to prevent sagging or overstretching of film **99**. In some embodiments, a handle **122** and/or feet **123** are provided so a person can manually handle the fragile film **98** more easily. (While film **98** is very strong compared to other materials of similar weight and length, multiple layers must be aggregated and/or embedded in a polymer to achieve noticeable strength on a macro scale.)

FIG. **1**J is a perspective schematic diagram of a first adhesive bar **131**, second adhesive bar **132** and third adhesive bar **133** being attached to a film **99** pulled from face **86** of a carbon-nanotube forest **89** using adhesive puller bar **199**.

FIG. **1**K is a perspective schematic diagram of a carbon nanotube film **98** held at its ends by first adhesive bar **131** and second adhesive bar **132** after removing the film **98** from the carbon-nanotube forest **89**, while the third adhesive bar **133** is used as adhesive puller bar **199** to pull an additional length of film **99** from a face of the carbon-nanotube forest **89**. In some embodiments, first adhesive bar **131** and second adhesive bar **132** are held at a fixed distance apart by a spacer bar similar to spacer bar **121** of FIG. **1**I. In some embodiments, a strong magnet **144** is positioned adjacent the face of substrate opposite where the nanotube forest **89** is being harvested. The nanotube formation process as described by Zhang et al. 2004 yields nanotube fibers with a purity of between 96 to 98% and 2 to 4% Fe and amorphous carbon. In some embodiments, an adhesion layer of nickel (Ni), titanium (Ti), vanadium (V), or some other suitable metal or composition is placed onto the nanoporous substrate (such as that disclosed in Zhang et al. 2004) and the iron (Fe) catalyst deposited thereon. The Fe layer is oxidized in order to form the catalyst. One purpose of this adhesion layer is to suppress separation of iron (Fe) or iron oxide from the catalyst layer and thereby placing impurities in the nanotube fiber. Keeping the iron oxide on the substrate also allows the substrate to be reused to grow more carbon nanotubes. In some embodiments, the strong north-south magnet **144** is placed, or a similar magnetic field is generated, under the substrate at or near the area of release (i.e., where the bases of the nanotubes are separating from the substrate) during the pulling of the nanotube film from the nanotube forest to attract the iron or iron compounds so as to prevent iron (Fe) from contaminating the nanotube fibers, by keeping iron on the surface of the nanoporous layer. In some embodiments, both the adhesion layer and the magnetic field are used to retain the catalyst material.

FIG. **1**L is a perspective schematic diagram of a stack **105** of carbon nanotube films **98**, each film in the stack **105** being held at its ends by a first adhesive sheet **110** and second adhesive sheet **111**, the films **98** stacked one upon another, in order to obtain a plurality of carbon-nanotube films **98** stacked to form a single thicker film structure. In some embodiments, one or more stacks of adhesive strips are used to generate a layered, thinned, and flattened nanotube structure. In these embodiments, a first adhesive strip is placed at each end of a nanotube film **98** drawn to a suitable length (e.g., 3 meters or other suitable length). A second nanotube film **98** is placed on top of the first single nanotube film **98**, and the adhesive strips holding its ends are placed on top of the adhesive strip holding the first film. This process is continued until a nanotube structure of a suitable number of layers is obtained. The suitability of a particular number of layers can be determined by empirical testing and/or modeling. As this nanotube structure **97** is completed, the stacks of adhesive strips **110** are built up at the ends of the structure **97**, layered one on top of another.

Once a nanotube structure of a suitable thickness is created, each stack of adhesive strips **134** and **135** is turned or bent to an angle of ninety (90)-degrees to the nanotube structure such that it is perpendicular to the length of the nanotube structure **97** in a direction opposite that of the other end. In some embodiments, the angle to which both the stack of adhesive strips and substrate are bent is greater than ninety (90) degrees. The optimum angles can be determined through empirical testing or modeling. Thus, in some embodiments, the stacks of adhesive strips **134** and **135** are bent to ninety-degree angles to the film stack **97** in directions opposite from one another (and perpendicular to the nanotube structure **97**).

FIG. **1**M is a perspective schematic diagram of method **106** to form a flattened or densified stack **97** of carbon nanotube films **98**, the stack **97** held at its ends by the respective first stack **135** of first adhesive sheets **110** and second stack **134** of second adhesive sheets **111**, which, in some embodiments, are each folded at a right angle to film stack **97** (in some embodiments, one stack (e.g., stack **135**) is folded up and the other (e.g., stack **134**) folded down, in order to keep all films **98** at the same length and tautness).

In some embodiments, as a result of bending the first and second stacks of adhesive strips such that their ends are coplanar, the layered nanotube structure will be condensed, thinned and flattened, and the strength of the nanotube structure will be increased due, in part, to very high surface-to-volume ratio between the various layers of single nanotubes (i.e., by the nanotubes of the parallel layers sticking to one another across greater surface areas). Specifically, a greater portion of the surface area of a single nanotube will come into contact with the a greater portion of the surface area of a second single nanotube, and the second nanotube sheet will come into contact with a third, and so on and so on, resulting in a very strong layered and flattened nanotube structure.

FIG. **1**N is a perspective schematic diagram of a flattened or densified stack **97** of carbon nanotube films **98** being removed from the respective stacks **134** and **135** of adhesive sheets **111** and **110** by other adhesive-sheet members **136** and **137**. In some embodiments, the adhesive **112** on adhesive-sheet members **136** and **137** will stick to all layers of film stack **97**, and the film ends attached to stacks **134** and **135** can be cut or torn off.

FIG. **1**-O is a perspective schematic diagram of a flattened or densified stack **97** of carbon nanotube films being held at their ends only by adhesive-sheet members **136** and **137**. In some embodiments, the resulting stack is densified by placing film stack **97** on a surface, applying a liquid, and having the liquid evaporate to draw the fibers together by surface tension. In some embodiments, the densification is performed with the stack of films **97** held on a sheet or backing, and in some embodiments, is performed on an endless belt such as shown in FIG. **10**E.

In at least one embodiment, a series of layered and flattened nanotube structures **97**, e.g., created using the method described above, is used to form a further nanotube structure in a cross-hatch pattern as described in FIGS. **2**A-**2**E below. In some embodiments, the above described layered and flattened nanotube structures **97** are used to form a nanotube structure in a cross-layer pattern. In some embodiments, a parallel-oriented layered nanotube structure is created. A plurality of these layered nanotube structures is then placed into a cross-hatch, cross-layer, woven or some other pattern. Once placed into one of these patterns, the adhesive-strip stack and substrates are folded to densify the nanotube structure in the above described manner. The result of this bending is that these nanotube structures that make up the above described patterns are flattened and densified, and hence stronger than they would otherwise be.

FIG. **1**P is a perspective schematic diagram of a flattened or densified stack **97** of carbon nanotube films **98** being removed from the respective stacks **134** and **135** of adhesive sheets by adhesive-bar members **138** and **139** having adhesive coatings **115**.

FIG. **1**Q is a perspective schematic diagram of a flattened or densified stack **97** of carbon nanotube films **98** being held only by adhesive-bar members **138** and **139**.

FIG. **1**R is a perspective schematic diagram of a splice process **107** in which a first carbon nanotube film **99** being pulled from a first carbon nanotube forest **89** about to be spliced to a second carbon nanotube forest **89'** using splicer bar **130**. In some embodiments, splicer bar **130** includes a non-adhesive front nose **141** configured to press film **99** into approximately the center of front face **86'** of forest **89'**. In some embodiments, front nose **141** includes a porous front surface (see FIG. **14**A) through which a vacuum is selectively applied in order to hold and later release film **99** during the splice process **107**. Some embodiments of splice bar **130** also include a cutting edge **142** for severing the initial film **99** once the splice has been made.

FIG. **1**S is a perspective schematic diagram of a first carbon nanotube film **99** from a first carbon nanotube forest **89** being spliced to a second carbon nanotube forest **89'**.

FIG. **1**T is a perspective schematic diagram of carbon nanotube film **99'** being pulled from the second carbon nanotube forest **89'** after being spliced and removed from the first carbon nanotube forest **89**. Splicer bar **130** is being withdrawn.

In some embodiments, a small amount of forest **89** and a small film tail **92** may remain unused, and may be removed and recycled as ordinary carbon nanotube material. Once the remaining forest **89** is removed from substrate **77**, additional carbon nanotube forest can be re-grown from catalyst surface **79**, which, in some embodiments, may or may not be porous. It is believed that when a nanotube is grown from a catalyst-covered porous surface such as described herein, each MWNT grows from its base at or near the iron-oxide catalyst. It is believed that when a nanotube film is pulled from a nanotube forest, the MWNTs break at or near the iron-oxide catalyst (where the molecular bonds are perhaps not as strong and/or not aligned as they are elsewhere in each MWNT). This would typically leave most or all of the catalyst attached to the growth surface, available to catalyze further growth if the substrate is again placed in a growth furnace and supplied with carbon-bearing source gas.

FIG. **1**U is a perspective schematic diagram of a system **108** wherein a first carbon nanotube film **99** being pulled from a first carbon nanotube forest on the top of a first double-sided substrate **76** is about to be spliced to a second carbon nanotube forest **89'** on the top of a second double-sided substrate. In the embodiment shown, a bottom-side nanotube forest **81** is grown on the opposite-face growing surface **78**, at the same time as top-side forest **89** is grown on top-side growing surface **79** of double-sided substrate **76**. At a later time, substrate **77** may be flipped and a film **99** may be spliced to its nanotube forest **81**. At a still later time, substrate **77'** may be flipped and a film **99** may be spliced to its nanotube forest **81'**. In this manner, a much longer film can be pulled than if the film **99** is pulled from only a single substrate **77**.

FIG. **1**V is a perspective view of a film-holder opener **185** for a clamping holder such as a split rubber tube. In some embodiments, film-holder opener **185** includes a bulb nose **186** to insert into the hollow core **183** of a clamping holder **181** (see FIG. **1**Z), opposing separating surfaces **189** for holding the slit **182** of clamping holder **181** open as it is slid past film-holder opener **185**. Opening **187** provides a space in which to insert film **98**, for example by air flow (either pressure from outside or vacuum from inside). In some embodiments, pressurized air is directed through nozzle **188** (see FIG. **1**Z), in order to push a film **98** through opening **187** and thus into film-holder **181**. In some embodiments, a vacuum is applied to the conduit extending from the top of film-holder opener **185** in order to suck a film **98** through opening **187** and thus into film-holder **181**. In some embodiments, the bottom of film-holder opener **185** is open from the film-depositing area and downstream in order that more of the film **98** comes in contact with the walls of hollow core **183**, so that the film **98** moves with and is gripped by film-holder **181** rather than sticking to film-holder opener **185**. In some embodiments, a flat surface **179** is provided next to film-holder opener **185** and supports film **98** as it is inserted into opening **187**, wherein surface **179**, film **98**, and film-holder **181** do not move laterally relative to one another during the insertion process. Film-holder opener **185** is then moved towards the right (in the orientation shown the drawing), and slot **182** closes, thus gripping film **98**. FIG. **1**W is a top view of the film-holder opener **185**. FIG. **1**X is an end view of the film-holder opener **185**. FIG. **1**Y is a side view of the film-holder opener **185**.

FIG. **1**Z is a perspective schematic diagram of a carbon nanotube film **99** being inserted into a clamping film-holding-bar **181**, such as a split rubber tube, for example. In some embodiments, a clamping film-holding-bar **181** includes a tube made of synthetic rubber or other elastomeric material having a hollow core **183** (which helps keep film-holding-bar **181** on film-holder opener **185** as it is slid right-to-left (in the orientation shown the drawing)) and a slit **182**. In some embodiments, film-holder opener **185** (the embodiment shown in FIG. **1**Z is slightly different than that of FIGS. **1**V-**1**Y) has a bulb nose **186** and a top slot **187**, which holds the slit **182** open as the film **98** is inserted. In some embodiments, pressurized air is directed through nozzle **188** to push a film **98** through opening **187** and thus into film-holder **181**. In some embodiments, a vacuum is applied to the conduit extending from the top of film-holder opener **185** in order to suck a film **98** through opening **187** and thus into a film-holder **181**.

FIG. **2**A is a perspective schematic diagram of a system **200** and a method for assembling a plurality of carbon nanotube films **98** into a wider structure **95**, each film **98** in the assembled structure **95** being held at its ends by a first adhesive rod, band or other or member **231** and second adhesive rod, band or other or member **232**, the films **98** placed one next to another and each transferred from its respective transportation holder **230**, in order to obtain a plurality of carbon-nanotube films placed to form a single wider and/or woven film structure **95**. In some embodiments, each transportation holder **230** includes a first adhesive member **131** at one end and a second adhesive member **132** at the other end, each attached to a rod or other structure to keep them at a constant distance to prevent sagging or stretching of film **98**. In some embodiments, as transportation holder **230** is pressed downward, adhesive member **131** drops below adhesive member **231** on its outside (right) edge, and adhesive member **132** drops below adhesive member **232** on its outside (left) edge, such that film **98** sticks to the adhesive surfaces of adhesive member **231** and adhesive member **232**, whereupon further pressing down pulls or tears film **98** from adhesive member **131** and adhesive member **132**. In other embodiments, a cutter is provided to cut the film **98** from adhesive member **131** and adhesive member **132**. In some embodiments, a plurality of layers of films **98** are stacked one upon another. In some embodiments, an overlap is provided between adjacent films **98**.

In some embodiments, members **131**, **132**, **231**, and/or **232** use a liquid coating (such as ethanol or water or oil or other suitable chemical or mixture) rather than an adhesive coating to hold carbon nanotube film **98** (e.g., by surface tension).

FIG. **2**B is a perspective schematic diagram of a system **202** and a method for criss-cross assembly of carbon nanotube films **98**. In some embodiments, each film **98"** in a first direction **215** (e.g., the X direction) being held at its ends by a first adhesive member **231** and second adhesive member **232**, the films **98"** placed one next to another and each transferred from its respective transportation holder **230** as described for FIG. **2**A (although small gaps between films **98** are shown in some of the figures throughout this application for clarity, in some embodiments, the films are tightly spaced and/or overlapped such that no such gaps are in the completed product). In some embodiments, each film **98'** in a second direction **216** (e.g., the Y direction) is being held at its ends by a third adhesive member **233** and fourth adhesive member **234**, the films **98'** placed one next to another and each transferred from its respective transportation holder **235** in a manner such as described for FIG. **2**A, in order to obtain a criss-crossed-film structure **94** made of a plurality of carbon-nanotube films. In some embodiments, the films are deposited in an order A, A, B, B, C, C, D, D, and so on. In some embodiments, after one complete layer **94** is deposited, one or more additional layers are stacked on the earlier layer(s).

FIG. **2**C is a perspective schematic diagram of a loom system **204** that provides a woven assembly **93** of carbon nanotube films **98**, each weft film **98'** in the woven assembly **93** being held at its ends by a first and adhesive member **233** second adhesive member **234**. Each warp film **98"** is held at the right-hand end by adhesive member **239** (also called the cloth beam), and at its opposite (left-hand) end by one loom rod of the moving sets of loom rods **236** and **246**. The warp films **98"** marked A (e.g., every other warp film) are each connected to an adhesive-covered portion of a respective one of loom rods **246**, and the warp films **98"** marked B (e.g., the other set of every other warp film) are each connected to an adhesive-covered portion of a respective one of loom rods **236**. Loom rods **236** and **246** alternately move up and down, as in a cloth loom, and between each movement, a weft film **98'** is inserted sideways (lower left to upper right, then rightward in the figure), but then adhesively attached to adhesive member **234** and adhesive member **235**.

For the various embodiments described herein, any of the described film-holding members (including those that operate by vacuum (see FIG. **14**A) or surface tension of a liquid to hold the carbon nanotube film to a surface, those that clamp the film between two surfaces (see FIG. **1**Z), as well as those members having an adhesive surface) can be substituted for one or more of the film holders called adhesive members.

FIG. **2**D is a perspective schematic diagram of a system **205** and a method of assembly of carbon nanotube films **98**, each film **98"** in a first direction being held at its ends by a first adhesive member **237** and second adhesive member **238** (in some embodiments, each having an adhesive coating **115**), each film **98'** in a second direction also being held at its ends by the first adhesive member **237** and second adhesive member **238**, the films placed one next to another and each transferred from its respective transportation holder **235** as described above, in order to obtain a crossed-film structure **93** of a plurality of carbon-nanotube films **98** in a continuous web. In some embodiments, the first adhesive member **237** and second adhesive member **238** are closed loops that are driven parallel to one another (e.g., on pulleys—see, for example, FIG. **10**A, FIG. **11**A, and FIG. **12**A) to move in a conveyor-belt fashion so the continuous web **93** of criss-crossed films is obtained.

FIG. **2**E is a perspective schematic diagram of continuous-loop loom **206** that provides a continuous web of woven carbon nanotube films, each film in the assembly being held at its ends by a first adhesive member **239** and a second adhesive member **238**, in order to obtain a woven-film structure **92** of a plurality of carbon-nanotube films in a continuous web. In the embodiment shown, the left adhesive conveyor-loop band **239** is designated the cloth beam **239** and the B warp films are attached from this cloth beam to the loom rods **236** alternating with the A warp films that are attached from this cloth beam **239** to the loom rods **246**. In some embodiments, since the free movable portions of the warp films **98"** get shorter as the conveyor moves to the left, the loom rods **236** and **246** towards the left (downstream) do not move up and down as much as those to the right (upstream). Once a downstream warp film **98"** has completed its weaving, it is attached to adhesive member **238** and its loom rod (**236** or **246**) is moved to the upstream end and a new film **98** is attached as warp film **98"** to it and to cloth beam **239** from transportation holder **235**. Between each loom rod movement, a weft film **98'** is inserted to the shed between the A films and the B films (shown by solid-line arrows), and attached to the conveyor-belt cloth beam **239** at one end and to the conveyor belt **238** at the other end. Its transportation rod **235'** is then withdrawn, new warp film **98"** is attached to the upstream loom rod **236** that is now empty and to the cloth beam **239** (shown by solid-line arrows) and detached from its transportation rod **235** (which is then removed), and the loom rods **246** that were down move up, and the loom rods **236** that were up move down. The next weft film **98'** is then inserted. This process is unique in that, in some embodiments, the cloth beam adhesive member **239** is used to attach and convey the first end of every warp film **98"** and the first end of every weft film **98'**, while adhesive member **238** is used to attach and convey the second end of every warp film **98"** and the second end of every weft film **98'**, and adhesive member **239** and adhesive member **238** can be moved in parallel as a conveyor belt to generate a continuous web **90** of woven carbon nanotube films **98**. In other embodiments, carbon nanotube threads or yarns (e.g., see FIG. **13**B) are substituted for carbon nanotube films **98**, and in some embodiments, are dispensed continuously from spools to the respective conveying adhesive members **238** and **239**, as can be understood by a person skilled in the art.

In other embodiments, threads such as nanotube threads **1398** (such as described in FIG. **13**B), or previously woven nanotube structures (such as web **1193** of FIG. **11**F, or a densified stack of parallel films **97** such as in FIG. **1**-O) are substituted for the nanotube films **98** of FIG. **2**C, **2**D or **2**E. That is, in some embodiments, nanotube threads are woven by attaching (in some embodiments, adhesively, or in other embodiments, with a vacuum) warp threads to a cloth bar (such as conveyor belt **239**) at one end (the far end) and to a loom rod at the other end (the near end), the loom rod being a member of one of a plurality of loom-rod sets. Wefts are inserted between the alternate up-and-down movements of the warps, and attached at their ends to holders **237** and **238** (see FIG. **2**D), or holders to holders **239** and **238** (see FIG. **2**E) to achieve the desired weave. When, in an embodiment such as FIG. **2**E, a warp thread or film is finished (all the wefts to be woven with that warp have been woven), the near end of that warp is attached to belt **238**, and a new warp thread or film is attached from belt **239** to a warp loom rod (e.g., the rightmost rod **246** in FIG. **2**E) at the other side of the warps. In this way, the wefts are sequentially placed parallel to one another and attached at a first diagonal angle between adhesive belt **238** at their near end and adhesive belt **239** at their far end and woven with the warps, which are sequentially placed parallel to one another and attached at a second diagonal angle between adhesive belt **239** at their far end at the start of their weaving and adhesive belt **238** at their near end at the finish of their weaving.

FIG. **2**F is an end view schematic diagram of continuous-loop loom **206**, showing the shed between the warp films **98"** connected to loom rods **236** and the warp films **98"** connected to loom rods **246** into which the weft film **98'** is inserted.

FIG. **3**A is a perspective schematic diagram **300** of a carbon nanotube film **99** being pulled from a carbon nanotube forest **89** having a gap **389** in the nanotube forest **89**. Such a gap **389** will cause a lengthwise gap in the midst of film **99**, and when the side films have been pulled even with the back of the gap, there may be an island of nanotube forest behind the gap to which the films are unable to pull nanotubes, further lengthening the lengthwise gap in the midst of film **99**.

FIG. **3**B is a perspective schematic diagram of a repair method for a possible gap in a carbon nanotube film **99** being pulled from a carbon nanotube forest **89** having a gap **389** in the nanotube forest **89** in a manner that suppresses any gap in the film. In some embodiments, both the puller member **199** and the substrate **77** are rotated nearly 90 degrees or more in the same rotational direction (e.g., clockwise), and the pull then continues at that acute angle until the pull reaches the end of gap **389**, whereupon the puller member **199** and the substrate **77** are rotated back the nearly 90 degrees or more in the same rotational direction (e.g., counterclockwise) to the orientation shown in FIG. **3**A. When the substrate **77** and puller member **199** are in the rotated position of FIG. **3**B, so that the film from the far edge of the gap contacts or nearly contacts the forest **89** at the near end of the gap, the film can be gap-free or nearly so. Further, the rotated orientation prevents the formation of a forest island (as described above) behind the gap.

In some embodiments, a forest-merging press arm **665** (such as described below for FIG. **6**C) is selectively moved when needed to press together the forest portions across a gap **389**. This can be used to press across small gaps within a nanotube forest **89**, such as can occur due to defects in the catalyst surface or other reasons. This pressure or contact between forest portions allows for the continuous or gap-free collection of the nanotube film **99** even if there is a slight gap due catalyst defects, flow-through defects or growing conditions in the nanotube forests **89**.

In some embodiments, the present invention provides substantially continuous growth and harvesting of carbon-nanotube forests on one or more synthesis substrates within a carbon-nanotube forest "farm" chamber. In some embodiments, each synthesis substrate is reused for a plurality of growth cycles, wherein the substrate, having one or more catalyst-covered faces, is placed in a reaction chamber in a furnace (e.g., in some embodiments, operating at about 680 degrees C.) and a carbon-bearing precursor or reactant gas (e.g., in some embodiments, 5 mol % acetylene in a Helium carrier) is provided to the vicinity of the catalyst-covered face(s). In some embodiments, an interior-flow synthesis substrate is used, wherein the reactant gas is supplied through a face opposite the growth surface (called a flow-through substrate—see, e.g., FIG. **9**F, **5**B or **8**K) or through a side face (called a side-flow substrate—see, e.g., FIG. **9**J or **5**F). In some embodiments, a nanotube film **99** is pulled directly from the nanotube forest **89** through an access port (e.g., **414**) into the reaction chamber (e.g., **412**) while the substrate **77** remains in the furnace (e.g., **410**). In some embodiments, the forest **89** and substrate **77** remain at about the growth temperature (e.g., 680 degrees C.) while nanotube film **99** is pulled, while in other embodiments, the forest **89** and substrate **77** are cooled at least somewhat before nanotube film **99** is pulled (e.g., in various of the embodiments, to about 650° C. or higher, to about 625° C. or higher, to about 600° C. or higher, to about 575° C. or higher, to about 550° C. or higher, to about 525° C. or higher, to about 500° C. or higher, to about 475° C. or higher, to about 450° C. or higher, to about 425° C. or higher, to about 400° C. or higher, to about 375° C. or higher, to about 350° C. or higher, to about 325° C. or higher, to about 300° C. or higher, to about 275° C. or higher, to about 250° C. or higher, to about 225° C. or higher, to about 200° C. or higher, to about 175° C. or higher, to about 150° C. or higher, to about 125° C. or higher, to about 100° C. or higher, to about 75° C. or higher, or to about 50° C. or higher), while in yet other embodiments, the forest **89** and substrate **77** are cooled to about room temperature before nanotube film **99** is pulled. In other embodiments, a substrate **77** and its nanotube forest are withdrawn through access port (e.g., **414**) from reaction chamber (e.g., **412**) while one or more other substrates remain in the reaction chamber at about the growth temperature (e.g., 680 degrees C.). The methods of the present invention thus allow continuous or substantially continuous growth and harvesting of nanotube forests **89**.

FIG. **4**A is a perspective block diagram of a system **400** that illustrates the continuous synthesis and collection of nanotube films. Here, an input reactant gas **61** is shown flowing through an input gas inlet **408** into the interior of a furnace **410**. Within the furnace **410** is situated a reaction chamber **412**. Input reactant gas **61** is shown flowing into the interior of the reaction chamber **412**. Within the reaction chamber, the input reactant gas **61** comes into contact with a substrate **77** that is located within the reaction chamber **412**. The substrate has a growth surface **79**. Contact of the input reactant gas **61** with the growth surface **79** of the substrate **77** provides for the synthesis of a nanotube forest **89**. The nanotube forest **89** is shown as having a leading edge **86**, a trailing edge **88**, a top **87** and a bottom **85**. Also shown is a new growth nanotube forest **81**. The leading edge **86** of the nanotube forest is illustrated as being pulled into a nanotube film **99** by a pulling bar **199**. The nanotube film **99** passes through an access port **414** that is positioned in a side of the furnace **410**. The nanotube film **99** then passes through the passage of the access port **414** through a cooling jacket **416**.

In some embodiments, it is undesirable to have a direct sideways flow of gasses across the growing nanotube forest **89**. The reaction chamber **412**, with its closed upwind end and its open downwind end allows reaction gasses to readily diffuse into the growth zone while preventing a direct breeze. In some embodiments, a gas pressure is maintained at access port **414** to also suppress any flow of gas through the access port. In some embodiments, an inverted-U-shaped heat trap is placed in the path of the access port **414**.

FIG. **4**B is a side view of system **400**. Input reactant gas **61** is shown flowing through an input gas inlet **408** into the interior of a furnace **410** in which a reaction chamber **412** is positioned. Within the reaction chamber **412** is shown a substrate having a growth surface **79** on which a nanotube forest **89** has been grown. Output exhaust gas **62** is shown flowing out of the furnace **410** through an exhaust outlet **409**.

FIG. **4**C is a top view of system **400** of the invention. Input reactant gas **61** is shown flowing through an input gas inlet **408** into the interior of a furnace **410** in which a reaction chamber **412** is positioned. Within the reaction chamber **412** is shown a substrate having a growth surface **79** on which a nanotube forest **89** has been grown. The nanotube forest **89** is illustrated as being pulled into a nanotube film **99** by a pulling bar **199**. The nanotube film **99** passes through an access port **414** that is positioned in a side of the furnace **410**. The nanotube film **99** then passes through a cooling jacket **416**. Output exhaust gas **62** is shown flowing out of the furnace **410** through an exhaust outlet **409**.

FIG. **5**A is a perspective block diagram of a system **500** that illustrates the continuous synthesis and collection of nanotube films using a method of the invention. Here an input reactant gas **61** is shown flowing through an input gas inlet **508** into the interior of a furnace **510**. The input reactant gas **61** passes through a flow-through substrate **75** that is located within the furnace **510** and contacts a growth surface **79** positioned on the flow-through substrate **75**. Contact of the input reactant gas **61** with the growth surface **79** of the flow-through substrate **75** provides for the synthesis of a nanotube forest **89** within a reaction chamber **512** positioned within the furnace **510**. The output exhaust gas **62** then exits the furnace through an exhaust outlet **509**. The nanotube forest **89** is shown as having a leading edge **86**, a trailing edge **88**, a top **87** and a bottom **85**. Also shown is a new growth nanotube forest **81**. The leading edge **86** of the nanotube forest is illustrated as being pulled into a nanotube film **99** by a pulling bar **199**. The nanotube film **99** passes through an access port **414** that is positioned in a side of the furnace **510**. The nanotube film **99** then passes through a cooling jacket **416**. Positioned within the furnace are baffles **520** that direct the flow of outlet exhaust gas **62** from the reaction chamber **512** to an exhaust outlet **509**. Also positioned within the furnace is a splicer-cutter **530** that is positioned above the leading edge of the new growth forest **81** that acts to cut the nanotube film from the old growth nanotube forest **82** and attach the nanotube film to the leading edge of the new **81**.

FIG. **5**B is a side view diagram of a system **501** that illustrates the continuous synthesis and collection of nanotube films using a method of the invention. Here an input reactant gas **61** is shown flowing through an input gas inlet **508** into the interior of a furnace **515**. The input reactant gas **61** passes through a flow-through substrate **75** that is located within the furnace **510** and contacts a growth surface **79** positioned on the flow-through substrate **75**. Contact of the input reactant gas **61** with the growth surface **79** of the flow-through substrate **75** provides for the synthesis of a nanotube forest **89** within a reaction chamber **512** positioned within the furnace **510**. The output exhaust gas **62** then exits the furnace through an exhaust outlet **509**. The nanotube forest **89** is shown as having a leading edge **86**, a trailing edge **88**, a top **87** and a bottom **85**. Also shown is a new growth nanotube forest **81**. The leading edge **86** of the nanotube forest **89** is illustrated as being pulled into a nanotube film **99** by a take-up reel **550**. The nanotube film **99** passes through an access port **514** that is positioned in a side of the furnace **510**. The nanotube film **99** then passes through a cooling jacket **416**. Positioned within the furnace are baffles **520** that direct the flow of outlet exhaust gas **62** from the reaction chamber **512** to an exhaust outlet **509**. Also positioned within the furnace is a splicer-cutter **530** that is positioned above the leading edge of the new growth forest **81** that acts to attach the nanotube film to the leading edge of the new growth nanotube forest **81** and cut the nanotube film from the old growth nanotube forest. The take-up reel **550** is positioned within a cooling box **511** that is continuously connected to the access port **514**. A pulling bar **199** is also positioned within the cooling box **511** that can be contacted with the leading edge **86** of a nanotube forest **89** to initiate formation of nanotube film **99**. The cooling box **511** is illustrated as having a gas inlet **552** to provide input of gas (e.g., inert gas) to provide backpressure in the cooling box **511** relative to the furnace **510** (to prevent passage of reactant gasses and heat) and relative to the outside environment (to keep out oxygen and other contaminants). Also illustrated is movement **564** of the take-up reel **550** to change the angle of the nanotube film **99** as the leading edge **86** of the old growth nanotube forest **82** recedes toward the trailing edge **88** of the old growth nanotube forest **82** as the old growth nanotube forest **82** is collected.

FIG. **5**C shows a later stage of nanotube film **99** collection relative to FIG. **5**B. As illustrated, the leading edge **86** of the old growth nanotube forest **82** has receded toward the trailing edge **88** of the old growth nanotube forest **82** as the old growth nanotube forest **82** is collected. In addition, movement **564** of the take-up reel **550** is shown to illustrate movement of the take-up reel **550** so that the nanotube film **99** does not come into contact with the new growth nanotube forest **81**.

FIG. **5**D shows a later stage of nanotube film **99** collection relative to FIG. **5**C. As illustrated, the leading edge **86** of the old growth nanotube forest **82** has receded toward the trailing edge **88** of the old growth nanotube forest **82** as the old growth nanotube forest **82** is collected. The splicer-cutter **530** is positioned to attach the nanotube film **99** to the leading edge of the new growth nanotube forest **81**, and, in some embodiments, slice the nanotube film **99** from the old growth to provide for continuous collection of the nanotube film **99**. Slicing the nanotube film **99** produces a film tail **92** that represents the remainder of the old growth nanotube forest **82**. In addition, movement **564** of the take-up reel **550** is shown to illustrate movement of the take-up reel **550** so that the nanotube film **99** comes into contact with the new growth forest **81**.

FIG. **5**E shows a later stage of nanotube film **99** collection relative to FIG. **5**D. As illustrated, the nanotube film **99** has been attached to the leading edge of the new growth nanotube forest **81** to facilitate continuous collection of the nanotube film **99**. In addition, movement **564** of the take-up reel **550** is shown to illustrate movement of the take-up reel **550** so that the nanotube film **99** comes into contact with the new growth forest **81**. This action transforms the formerly new growth nanotube forest **81** into the old growth nanotube forest **82** to continue the synthesis and collection cycle.

FIG. **5**F is a side view diagram of a system **505** that implements a method of some embodiments of the invention, which provides for nanotube synthesis on multiple double-sided flow-through substrates **74**. Input reactant gas **61** is shown flowing through a side-inlet **508** into the interior of a furnace **515**. The input reactant gas **61** passes through a double-sided flow-through substrate **74** that is located within the furnace **515** and contacts a growth surface **79** positioned on the double-sided flow-through substrate **74**. Contact of the input reactant gas **61** with the growth surface **79** of the double-sided flow-through substrate **74** provides for the synthesis of a nanotube forest **89** within a reaction chamber **512** positioned within the furnace **515**. The outlet exhaust gas **62** then flows through a side-outlet **509**.

In some embodiments, the source reactant gas **61** includes acetylene in a helium carrier, and the exhaust or output gas **62** includes some of the acetylene, the helium carrier, and waste byproducts of the nanotube synthesis reaction such as hydrogen gas and/or other hydrocarbons. In some embodiments, the exhaust gasses are recycled, e.g., by compressing and separating the gasses, then remixing the recovered acetylene and helium carrier, adding supplemental new gasses as needed, and using the result as input reactant gas **61**.

FIG. **5**G is a side view diagram of a system **506** that implements a method of some embodiments of the invention, which provides for nanotube synthesis on an extended basis from flow-through substrates **74**. Input reactant gas **61** is shown flowing through a side-inlet **508** into the interior of a furnace **515**. In some embodiments, the input reactant gas **61** passes through a double-sided flow-through substrate **74** that is located within the furnace **515** and contacts a growth surface **79** positioned on the double-sided flow-through substrate **74**. Contact of the input reactant gas **61** with the growth surface **79** of the double-sided flow-through substrate **74** provides for the synthesis of a nanotube forest **89** within a reaction chamber **512** positioned within the furnace **515**. The outlet exhaust gas **62** then flows through a side-outlet **509**. In some embodiments, a puller bar **590** is attached (e.g., using a suitable pressure-sensitive adhesive), and operated by weight and/or servo control to gently pull on the tops (i.e., the end distal to the growing surface **79** of substrate **594**) in a direction **591**. In some embodiments, direction **591** is substantially vertical and downward. In other embodiments, direction **591** is upward. In some embodiments, substrate **594** is porous to allow reactant gasses **61** access to growing surface **79**. In some embodiments, exhaust ports **509** are provided through puller bar **590**.

FIG. **5**H is a cross-section side view schematic of a carbon-nanotube synthesis apparatus **507** having a heat trap **576**. In some embodiments, nanotube film **99** is passed across one or more rollers **577** in a raised portion (heat trap **576**) of access port **514**. In some embodiments, hot gasses and/or helium (in embodiments that use helium in the process) and/or less dense gasses, from furnace **590** (which can be any of the furnaces described herein such as **510** described above or **610** described below) will tend to rise to the top of heat trap **576**, while the cooler and/or more dense gasses (e.g., argon) remain in the cool box **518**. In some embodiments, the vertical rise used by heat trap **576** is up to a meter or more, (e.g., in some embodiments, about 0.5 meters or more, about 1 meter or more, about 2 meters or more, about 3 meters or more, about 4 meters or more, about 5 meters or more, about 6 meters or more, or about 7 meters or more) in order to suppress gas diffusion effects that might otherwise cause undesired gas to flow through port **514**. Thus, in some embodiments, such a heat trap is used in a passageway through which nanotube film **99** is passing, while in other embodiments, such a heat trap is used for a passageway through which nanotube forests **89** on substrates **77** are passing.

FIG. **6**A is a side view block diagram of a system **600** that illustrates the continuous synthesis and collection of nanotube films using a method of the invention. Here, an input reactant gas **61** is shown flowing through an input gas inlet **608** into the interior of a reaction chamber **612** that is positioned within a furnace **610**.

In some embodiments, at least one substrate **74** of the plurality of substrates **74** in linked-substrate loop **674** is a flow-through nanoporous substrate such as described in FIG. **8**J, FIG. **8**P, FIG. **9**F, or FIG. **9**J. In other embodiments, a conventional non-flow-through substrate is used such as described in U.S. Pat. No. 6,232,706 or the articles listed above as Zhang et al. 2004 or Zhang et al. 2005. In yet other embodiments, non-porous substrates, such as rough- or smooth-textured silicon wafers are used.

In some embodiments, the input reactant gas **61** passes through distribution baffles **621** and then through one or more side-by-side flow-through linked substrates **74** that are located within the reaction chamber **612** of the furnace **610**. In some embodiments, reaction chamber **612** forms, or is moveable to form, a fairly tight seal around the bottom of the substrates in the reaction chamber **612** (e.g., **6747**, **6746**, and **6745** in the embodiment shown) in order to force the gas through the flow-through substrate(s) (or into the sides of a side-flow substrate, in other embodiments). By providing a flow-through substrate, reactant gas reaches all parts of the growing forest, such that nanotubes near the edges grow at about the same rate as nanotubes on the center of the forest, thus avoiding forests with concave tops that grow that way because they do not have sufficient gas reaching the center of the forest due to blockage from the nanotubes around the edge. The input reactant gas **61**, upon reaching the top of substrate **74**, contacts a catalyst-covered growth surface **79** on the flow-through linked substrate **74**. Contact of the input reactant gas **61** with the catalyst on growth surface **79** of a substrate **74** in the linked-substrate loop **674** provides for the synthesis of nanotube forests **89** within a reaction chamber **612** that is positioned within the furnace **610**. It is believed that growth occurs at the bottom of each nanotube (i.e., next to the catalyst). The exhaust or output gas **62** then exits the furnace through an exhaust outlet **609**.

The nanotube forests **89** are shown as having a leading edge **86**, a trailing edge **88**, a top **87** and a bottom **85**. The linked-substrate loop **674** includes individual substrates **74** that are linked by substrate connectors **662**. The linked-substrate loop **674** forms a continuous loop that can be intermittently or continuously advanced. As the loop is advanced, the individual linked flow-through substrates **74** pass through a preheat furnace **618** that is included within the furnace **610**, enter into a reaction chamber **612** where synthesis of nanotube forest **89** occurs, exit the reaction chamber **612** through an access port **614** in the side of the furnace **612**, pass through a cooling jacket **616**, have their nanotube forests **89** harvested, and then reenter the furnace through another access port **615** after their forests **89** have been harvested.

In some embodiments, linked-substrate loop **674** forms a continuous loop that can be continuously advanced, or in other embodiments, the loop is advanced (for example, by the length of the center-to-center distance between substrates **74**) and then substantially stopped for a period of time. For example, in the embodiment shown, three substrates are in growth chamber **612** at any one time, and each substrate **74**, after entering reaction chamber **612** spends one-third of its growth time in the position of substrate **6747**, the next one-third of its growth time in the position of substrate **6746**, and the last one-third of its growth time in the position of substrate **6747** (e.g., in some embodiments, about 200 seconds in each station for a total of ten minutes). In some embodiments, the substrates **74** are cooled at least somewhat by resting in cooling jacket **616** while subsequent substrates **74** grow their nanotube forests **89** in reaction chamber **612**.

In some embodiments, after an individual substrate **74** passes through the cooling jacket **616**, the leading edge **86** of the nanotube forest **89** grown on a leading (i.e., an initial) individual substrate **74** is contacted with a pulling bar **630**. The pulling bar **630** (which, in some embodiments, has an adhesive front surface such as shown in FIG. **1**D, a vacuum front surface as shown in FIG. **14**B, or other suitable film-pull-starting mechanism) pulls the leading edge of nanotube forest **89** from substrate **6741** to form a nanotube film **99**. In some embodiments, the nanotube film **99** is attached to be wound around rotating take up reel **650**. The pulling bar **630** is then retracted and the take up reel **650** turns in direction **651** to continuously pull and take up the nanotube film **99** from the individual linked substrate **74** and form nanotube-film spool **652**.

In some embodiments, when the continuous closed loop of linked-substrate loop **674** is advanced (or advanced and then stopped), the portion of continuous loop **674** immediately next to the film pull (i.e., substrate **6741**, which has the nanotube forest **89** that is currently being harvested into film **99**, and substrate **6742** that has the nanotube forest **89** that will next be harvested) is bent inward to form a folded junction **660** where the trailing edge **88** (see FIG. **1**A) of the preceding nanotube forest **89** on substrate **6741** is placed into contact with the leading edge **86** of the following nanotube forest **89** on substrate **6741**.

FIG. **6**B is a close-up side view of the folded junction **660** of FIG. **6**A. It illustrates the nanotube film **99** being pulled and collected from the leading edge **86** of a nanotube forest **89** on linked substrate **6741** as the trailing edge **88** of that nanotube forest **89** is being placed into contact with the leading edge **86** of another nanotube forest **89** grown on the next following linked substrate **6742** at a folded junction **660**. This intimate contact allows the film harvest to jump from the depleted nanotube forest on linked substrate **6741** to the unharvested forest on linked substrate **6742**, for the continuous collection of the nanotube film **99** from the individual linked substrates **74** of the advancing linked-substrate loop **674**.

FIG. **6**C is a side-view diagram of a system **602** that provides the continuous synthesis and collection of nanotube films used by a method of the invention. In some embodiments as shown, an input reactant gas **61** is flowing through an input gas inlet **608** into the interior of a reaction chamber **612** that is positioned within a furnace **610**. The input reactant gas **61** passes through distribution baffles **62** and then through linked substrates **74** that are located within the reaction chamber **612** of the furnace **610**. The input reactant gas **61** contacts a growth surface **79** positioned on the linked substrates **74**. Contact of the input reactant gas **61** with the growth surface **79** of the linked substrates **74** provides for the synthesis of nanotube forests **89** within the reaction chamber **612** that is positioned within the furnace **610**. The nanotube forests **89** are shown as having a leading edge **86**, a trailing edge **88**, a top **87** and a bottom **85**. The linked-substrate loop **674** includes individual substrates **74** that are linked by substrate connectors **662**.

In some embodiments, at least one linked substrate **74** in linked-substrate loop **674** is a flow-through nanoporous substrate such as described in FIG. **8**J, FIG. **8**P, FIG. **9**F, or FIG. **9**J. In other embodiments, a conventional non-flow-through substrate is used such as described in U.S. Pat. No. 6,232,706 or the articles listed above as Zhang et al. 2004 or Zhang et al. 2005. In yet other embodiments, non-porous substrates, such as rough- or smooth-textured silicon wafers are used.

In some embodiments, linked-substrate loop **674** forms a continuous loop that can be continuously advanced, or in other embodiments, the loop is advanced (for example, by the length of one linked substrate **74**) and then substantially stopped for a period of time. For example, in the embodiment shown, three substrates are in growth chamber **612** at any one time, and the substrates stop for a period of time (e.g., one-third of the nanotube growth time) in each position around the loop, then move one substrate length (i.e., by the center-to-center distance between linked substrates **74**) to the next position and again stop. In other embodiments, a slow continuous movement is used that moves the loop at a rate approximately equal to the rate of harvest at the front nanotube forest **89**.

In some embodiments, the already-harvested linked substrates re-enter furnace **610** and pass through an optional heat trap **649**, which suppresses convective heat flow. As the linked-substrate loop **674** is advanced, the individual linked flow-through substrates **74** pass through a preheat furnace **617** that is included within the furnace **610**, enter into reaction chamber **612** where synthesis (lengthwise growth) of nanotube forest **89** occurs, exit the reaction chamber **612** through a first access port **614** in the side of furnace **610**, pass through a cooling jacket **616**, pass through a second cooling jacket **618**, and then reenter the furnace through another access port **619**. After an individual substrate **74** passes through the cooling jacket **616**, the leading edge **86** of the nanotube forest grown on the individual substrate **74** is contacted with a pulling bar **630**. The pulling bar **630** pulls the nanotube forest **89** to form a nanotube film **99**. The nanotube film **99** is attached to and wound by a take up reel **650**. The pulling bar **630** is then retracted and the take up reel **650** turns **651** to continuously take up the nanotube film **99** from the individual substrate **74**. As the continuous loop **674** of linked substrates is advanced, the continuous loop **674** forms a folded junction **660** where the trailing edge **88** of the preceding nanotube forest **89** (on substrate **6741**) is placed into contact with the leading edge **86** of the following nanotube forest **89** (on substrate **6741**). In addition, in some embodiments, the nanotube forest **89** grown on preceding linked substrate **6741** is pressed into the leading edge of a nanotube forest **89** growing on the following linked substrate **6742** by a forest-merging press arm **665** which is selectively moved when needed to press the two forests together. This can be at the junction between different nanotube forests **89** on separate substrates **6741** and **6742** as shown, but, in some embodiments, can also be used to press across small gaps within a nanotube forest **89**, such as can occur due to defects in the catalyst surface or other reasons. This pressure or contact between forests allows for the continuous collection of the nanotube film **99** from the separate substrates **74** of the advancing continuous loop **674** even if there is a slight gap due to spacing between substrates and/or growing conditions at the edges of the substrates.

Also illustrated is an input gas inlet **607** positioned next to the take up reel **650** in some embodiments, and through which gas (e.g., an inert gas such as helium or argon, or other gas that does not detrimentally react with the warm or hot nanotube forests **89**) can flow to maintain a slight positive gas pressure that acts to exclude oxygen from the cool chamber **618** of the invention during collection of nanotube-film **99**.

FIG. **6**D is a side cross-section view diagram of a system **604** that provides continuous nanotube synthesis, wherein the chamber of furnace **610** is located generally above cool chamber **618**, in order to suppress convection between the chambers. The features are the same as, or similar to, like-numbered features described in FIGS. **6**A and **6**C.

FIG. **7**A is a side cross-section view diagram of a continuous nanotube synthesis device or system **700** of some embodiments of the invention. Here, an input reactant gas **61** is shown flowing into the interior of a closed-ended substantially cylindrical substrate **71** that is positioned within a furnace **710**. In some embodiments, cylinder substrate **71** has an outer layer formed of microporous ceramic of the type used to cold filter beer, for example having an inner structure and composition similar to the ceramic filters described in U.S. Pat. No. 6,394,281 by Ritland et al., which is incorporated herein by reference.

In some embodiments, the outer surface of the starting material is formed or machined to a substantially smooth outer surface in the shape of a cylinder. In other embodiments, the shape of a truncated cone or other solid prism shape is used. In some embodiments, this outer layer's surface is covered with a CVD-deposited layer of polysilicon, which is then treated with an anodic etch in ethanol and hydrofluoric acid to create a nanoporous surface as described above for silicon wafers, and then covered with a 5-nanometer (for example) layer of iron that is then oxidized to form the nanotube catalyst. This forms a flow-through substrate cylinder **71**. Other embodiments use other materials to create cylinders (that may be, but need not be, flow-through) that will operate at the high temperatures (e.g., 680 to 700 degrees centigrade, in some embodiments). In some embodiments that use a porous material for cylinder substrate **71**, the slightly pressurized input reactant gas **61** passes or permeates through the substantially cylindrical porous substrate **71** and contacts a catalyst-covered growth surface **79** located on the outside of substantially cylindrical substrate **71**. Interaction of the input reactant gas **61** with the catalyst-covered growth surface **79** of cylindrical substrate **71** provides for the synthesis of a radially-aligned, densely packed continuous nanotube forest **89** on the catalyst-covered growth surface **79**. This synthesis occurs within a reaction region **712** that is located within furnace **710**. In some embodiments, reaction region **712** includes a plurality of baffles **720**. In some embodiments, no reaction chamber enclosure is used since the nanotube forest is continuously grown in a radial direction as cylinder **71** rotates, and the nanotube film **99** is harvested continuously from front face **86** of forest **89** while still at the reaction temperature (e.g., 680 to 700 degrees centigrade, in some embodiments).

The nanotube forest **89** is shown as having a leading edge **86**, new growth nanotube forest **81**, a top **87** distal from growth surface **79** of cylinder **71**, and a bottom **85** adjacent to growth surface **79** of cylinder **71**. The exhaust or output gas **62** then exits the furnace **710** through an exhaust outlet **709**. In some embodiments, a leading edge **86** of the nanotube forest **89** is initially contacted with a pulling bar **630** that then withdraws from nanotube forest **89** to form and pull nanotube film **99**. In some embodiments, nanotube film **99** is attached to a take up reel **750**. The pulling bar **630** is then retracted and the take up reel **750** turns in direction **751** to continuously collect the nanotube film **99** from cylindrical substrate **71**. In some embodiments, cylindrical substrate **71** is very slowly turned as the nanotube film **99** is collected from the substrate to provide for continuous collection of the nanotube film **99**. In some embodiments, an optical sensor is connected to a servo motor used to rotate cylindrical substrate **71** in order to keep front edge **86** of nanotube forest **89** at an optimal position or angle for pulling the nanotube forest **89**. In some embodiments, nanotube film **99** passes through a side access port **714** in furnace **710** and through cooling jacket **716** into cool chamber **718** before it is collected on the take up reel **750** positioned within cooling box **711**. In some embodiments, cooling box **711** includes a positive-pressure gas inlet **752** that provides for entry of gas to maintain a positive pressure within the cooling box **711** that acts to exclude oxygen or other potential contaminants from the cooling box **711**. Also illustrated are insulation walls **713**.

FIG. **7**B is side cross-section view of system **701**, a variation where the take up reel **750** is positioned within the cooling box **711** such that the nanotube film **99** forms a forest-merge pull angle **731** from the normal vector to forest front face **86** (or the tangent vector to cylinder substrate **71**). In some embodiments, forest-merge pull angle **731** forces nanotubes on the leading edge **86** of the nanotube forest **89** into better contact with nanotubes that are slightly behind the leading edge **86**, in order to increase collection efficiency from the leading edge **86** of the nanotube forest **89**. In some embodiments, system **700** or system **701** also includes a press bar.

Some embodiments of the below methods use techniques as described in U.S. Pat. No. 6,428,713 to Christenson et al., entitled "MEMS sensor structure and microfabrication process therefor" which is incorporated herein by reference.

FIGS. **8**A-**8**K are perspective schematic diagrams of a substrate **877** going through steps in making a flow-through substrate for growing carbon nanotube forests **89**, this method used in some embodiments of the present invention. In FIG. **8**A, a substrate **877** (e.g., made of a silicon wafer having a 100-crystal orientation at its top surface) is overlaid by SiO_2 strips or islands **801** by well-known semiconductor-processing techniques. (E.g., in some embodiments, the top layer is thermally oxidized; the pattern is photo-lithographically defined, and etched to leave strips **811**. In some embodiments, one approach is to heat substrate **877** to a high temperature, for example, 850 to 1200 degrees C., in a controlled atmosphere containing either pure oxygen or water vapor. At such high temperatures, the oxygen and/or water vapor diffuse into and react with the silicon of substrate **877**, thereby forming a silicon dioxide layer on the exposed top surface of substrate **877**. This silicon dioxide is patterned into strips **811** that serve as a bonding oxide for epitaxial growth, as an etch-termination layer, and are later removed to leave lateral gas passages and an inner surface for the porous-etch process.) This results in partially processed substrate **800**. In some embodiments, strips **811** are periodically connected to one another with narrow bridges along their lengths or near their ends, in order that the gas passages that result from later processing are all connected to one another. Other materials can be substituted in other embodiments.

In FIG. **8**B, substrate **877** is processed to grow epitaxial single-crystal silicon **820** to the tops of SiO_2 strips **811** by well-known semiconductor-processing techniques. This results in partially processed substrate **801**.

In FIG. **8**C, substrate **877** has experienced further epitaxial single-crystal silicon growth laterally **822** over the edges SiO_2 strips **811** by well-known semiconductor-processing techniques (lateral epitaxial growth). This results in partially processed substrate **802**.

In FIG. **8**D substrate **877** has experienced further epitaxial single-crystal silicon growth laterally, completely covering SiO_2 strips **811**. This results in partially processed substrate **803** having an outer silicon surface **821** that is substantially covering at least one face of substrate **877**, wherein underlying at least a portion of the outer silicon surface **821** are silicon dioxide strips **811**.

In FIG. **8**E, substrate **877** has been covered with silicon dioxide, wherein the top surface is left completely covered with SiO_2 and the bottom has been patterned into SiO_2 strips **831**. This results in partially processed substrate **804**.

In FIG. **8**F, substrate **877** has been etched from the bottom. For example, in some embodiments, using deep reactive ion etching (DRIE), e.g., as described in U.S. Pat. No. 6,685,844 to Rich et al. and/or as described in U.S. Pat. No. 6,127,273 to Laermer et al., which are incorporated herein by reference. In some embodiments, an Alcatel 601 DRIE machine and a pulsed-gas process, as described in the just-mentioned patents, is used to form back channels **834** and leaving silicon beams **830**. In some embodiments, silicon cross beams **832** are also left. This results in partially processed substrate **805**. FIG. **8**G shows this result along section line **8**G.

FIG. **8**G shows a cross-section view of processed substrate **805** showing silicon cross beam **832** that was left. The bottom etch was stopped before penetrating top layer **821**.

In FIG. **8**H substrate **877** has been etched to remove substantially all the silicon dioxide. This results in partially processed substrate **806**, having upper channels **841** and bottom channels **834**. FIG. **8**I shows this result along section line **81**.

FIG. **8**I shows a cross-section view of processed substrate **806** showing silicon cross beam **832** that was left.

In FIG. **8**J, substrate **877** has been processed with a nanoporous etch as described above. E.g., in some embodiments, at least top layer **821** is a highly P-doped n^+ type silicon substrate (100-oriented-crystal top surface, resistivity 0.008-0.018 Ohm-cm), and is electrochemically etched in 1:1 HF (49% in water) ethanol with an anodization current density of 10 mA/cm^2 (in some embodiments, typical etching time is five minutes). This forms a thin nanoporous layer (pore size about 3 nanometers) on top of a microporous layer (pore size about 100 nanometers). In some embodiments, the other exposed surfaces of the channels are also affected similarly, and have a nanoporous surface. Next, in a step B, in some embodiments, the top of the porous layer is covered substantially in its entirety (unlike Dai et al. describe in U.S. Pat. No. 6,232,706) with a five-nanometer thick iron (Fe) film by e-beam evaporation. The inner and bottom surfaces are not iron coated, in order to prevent nanotube growth inside substrate **877**. In some embodiments, after deposition of iron, the substrate is annealed in air at 300 degree C. overnight. This annealing step oxidizes the surface of the silicon as well as the iron, converting the iron patterns into catalytically active iron-oxide. The resulting silicon dioxide layer formed on the underlying porous silicon prevents the porous structure of layers from collapsing during any following high-temperature chemical vapor deposition (CVD) step. This results in partially processed substrate **807**, having upper channels **841** and bottom channels **834**. The top growing surface **79** has an iron-oxide catalyst layer and a large plurality of nanopores that conduct reactant gasses from the bottom of substrate **807** through to the top layer **79**.

FIG. **8**K shows a cross-section view of processed substrate **807** showing silicon cross beam **832** that was left. The two-dimensional X-Y grid of beams **830** and **832** provide structural integrity to substrate **807**. In some embodiments, the cross beams **832** are at a slant angle to direction Y, in order that all passages **841** connect to at least one gas passage **834** through the back of substrate **807**. Region **871** represents where the bottom etch was stopped before eating through top layer **821**.

FIG. **8**L is a bottom-view schematic diagram of a flow-through substrate **807** for growing a carbon nanotube forest **89**.

FIG. **8**L**1** is a close-up bottom-view schematic diagram of a flow-through substrate for growing a carbon nanotube forest. In some embodiments, the cross beams **832** are at a slant angle to direction Y, in order that all passages **841** connect to at least one gas passage **834** through the back of substrate **807**.

FIGS. **8**M-**8**P are perspective schematic diagrams of alternative steps in making a flow-through substrate for growing carbon nanotube forests. In some embodiments, these steps represent processing done after that of FIG. **8**G.

FIG. **8**M is a perspective schematic view of a substrate **808**, wherein the nanopore etching described for FIG. **8**J above is performed before etching to remove silicon dioxide strips **811**, in order that the etching operation occurs only from the top surface of top layer **821** to form porous top layer **861**. FIG. **8**N shows this result along section line **8**N.

FIG. **8**N shows a cross-section view of processed substrate **808** showing silicon cross beam **832**.

In FIG. **8**O substrate **877** has been etched to remove substantially all the silicon dioxide of strips **811**. This results in completed substrate **809**, having upper channels **841** and bottom channels **834**. FIG. **8**I shows this result along section line **81**.

FIG. **8**I shows a cross-section view of completed substrate **809** showing silicon cross beam **832**.

FIGS. 9A-9G are perspective schematic diagrams of steps in making a flow-through substrate for growing carbon nanotube forests. The processing here is similar in some respects to that described in FIGS. **8**A to **8**K, except that narrow, deep channels **919** are used rather than the less-deep channels **811** used in FIGS. **8**A to **8**K.

In FIG. **9**A, a substrate **977** (e.g., made of a silicon wafer having a 100-crystal orientation at its top surface) deep etched to create grooves or channels **919** by deep reactive ion etching (DRIE), e.g., as described in U.S. Pat. No. 6,685,844 to Rich et al. and/or as described in U.S. Pat. No. 6,127,273 to Laermer et al., which are incorporated herein by reference. In some embodiments, an Alcatel 601 DRIE machine and a pulsed-gas process, as described in the just-mentioned patents, is used. Channels **919** will delineate lateral gas passages that extend in the Y direction in the final processed substrate, while reducing the lateral extent (the size of the top porous membrane between support pillars in the Z direction) of the nanoporous top surface in order to increase the strength of the top surface.

In some embodiments, as described below for FIG. **9**H, additional occasional cross channels **920** (e.g., along the X direction, left-to-right in the diagram and each connecting to a plurality of the channels shown (those extending in the Y direction, from lower left in the diagram to upper right)). In some embodiments, these cross channels **920** are wider than channels **919**, and thus etch deeper than channels **919**. In some embodiments, the cross channels **920** are positioned in a staggered manner along the Y direction, in order to prevent any straight channel completely crossing the substrate in the X direction, which could weaken the substrate along that line. In some embodiments, cross channels **920** are etched completely through substrate **977**, eliminating the need for, and the steps used to separately create, the back channels **915**, since the wider cross channels serve a similar purpose.

In FIG. **9**B, substrate **977** is processed to fill channels **919** and channels **920** with SiO_2. to form silicon dioxide strips **918**, which support the epitaxial lateral overgrowth (ELOG) of silicon top layer **930**, but will then later be etched away to leave lateral gas passages.

In FIG. **9**C substrate **977** has experienced epitaxial single-crystal-silicon growth laterally, completely covering SiO_2 strips **911**. This results in partially processed substrate **902** having an outer silicon surface **921** that is substantially covering at least one face of substrate **977**, wherein underlying at least a portion of the outer (e.g., top) silicon surface **921** are silicon dioxide strips **918** having a greater vertical extent than width, and extending lengthwise in the Y direction.

In FIG. **9**D, substrate **977** has been covered with silicon dioxide, wherein the top surface is left completely covered with SiO_2 and the bottom has been patterned into SiO_2 strips **931**. This results in partially processed substrate **804**. Further, substrate **977** has been etched from the bottom (for example, in some embodiments, using DRIE) to form back channels **915** and leaving silicon beams **939**. In some embodiments, silicon cross-beams extending in the Y direction or at an angle to the Y direction are also left, as described in FIG. **8**G. This results in partially processed substrate **903**. The bottom etch was stopped after the bottom channels **915** reach the silicon dioxide strips **918**, but well before penetrating top layer **921**. This provides greater strength than in FIG. **8**G, and is also easier to accomplish because the silicon dioxide strips **918** are so much deeper than silicon dioxide strips **811** of FIG. **8**G.

In FIG. **9**E substrate **977** has been etched to remove substantially all the silicon dioxide. This results in partially processed substrate **904**, having upper channels **918** extending in the Y direction and bottom channels **915** extending in the X direction.

In FIG. **9**F, substrate **977** has been processed with a nanoporous etch as described above for FIG. **8**G. The top growing surface **79** has an iron-oxide catalyst layer and a large plurality of nanopores that conduct reactant gasses from the bottom of substrate **977** through porous layer **951** to the catalyst-covered growth surface **79**. In some embodiments, the initial channels **919** are spaced far enough apart that the vertical walls are initially thick enough such that after nanopore etching creates porous layer **952**, there is still a wall of substantially solid silicon **953** to help support and strengthen top layer **951**. FIG. **9**G shows the resulting completed substrate along section line **9**G.

FIG. **9**G shows a cross-section view of processed substrate **905** showing silicon bottom cross beam **932** that was left after the bottom etch earlier. The two-dimensional X-Y grid of beams **915** and **932** provide structural integrity to substrate **905**. In some embodiments, the cross beams **932** are at a slant angle to direction Y, in order that all passages **917** connect to at least one gas passage **934** through the back of substrate **905**.

FIG. **9**H is a perspective-view schematic diagram of a partially processed substrate **906** that results after a substrate **978** (e.g., made of a silicon wafer having a 100-crystal orientation at its top surface) is deep etched to create grooves or channels **919** by deep reactive ion etching (DRIE), as described for FIG. **9**A. In some embodiments, additional occasional cross channels **920** (e.g., along the X direction in the diagram and each connecting to a plurality of the channels **919** that extend in the Y direction). In some embodiments, these cross channels **920** are wider, and thus etch deeper than channels **919**. In some embodiments, the cross channels **920** are moved back and forth along the Y direction, in order to prevent any straight channel completely crossing the substrate in the X direction, which could weaken the substrate along that line. In some embodiments, at least some of either channels **919** or channels **920** are etched out to a point that will be outside side wall **960** in the completed substrate, in order to provide a gas inlet port through a side wall of substrate **978**.

FIG. **9**I is a perspective-view schematic diagram of a partially processed substrate **907** after substrate **978** is processed to fill channels **919** and channels **920** with SiO_2 to form silicon dioxide strips **918** and **929**, which support the epitaxial lateral overgrowth (ELOG) of silicon top layer **921**, but will then later be etched away to leave lateral gas passages having at least one gas inlet port through a side wall **960** of substrate **978**. Further, substrate **978** has now experienced epitaxial single-crystal-silicon growth laterally, completely covering SiO_2 strips **918** and **929**. This results in partially processed substrate **907** having an outer silicon surface **921** that is substantially covering at least one major face of substrate **978**, wherein underlying at least a portion of the outer (e.g., top) silicon surface **921** are silicon dioxide strips **918** having a greater vertical extent than width, and extending lengthwise in the Y direction, and silicon dioxide strips **929** having a greater vertical extent than width, and extending lengthwise in the X direction to contact a plurality of strips **918**. Processing continues as described for FIGS. **9**A-**9**G.

FIG. **9**J is a perspective-view schematic diagram of a mostly processed substrate **908** after substrate **978** has been processed with a nanoporous etch as described above for FIG. **8**G. The top growing surface **79** has an iron-oxide catalyst layer and a large plurality of nanopores that conduct reactant gasses from the bottom of substrate **978** through porous layer **951** to the catalyst-covered growth surface **79**. In some embodiments, the initial channels **919** and **920** are spaced far enough apart that the vertical walls are initially thick enough such that after nanopore etching creates porous layer **952** (surrounding porous channels **965**), there are still walls **953** of substantially solid silicon to help support and strengthen top porous layer **951**.

FIG. **9**K is a perspective-view schematic diagram of a substrate **977** made into a side-flow or through-flow dugout substrate **981** for growing carbon nanotube forests. In the embodiment shown, dugout substrate **981** includes a plurality of long, deep, narrow slots **971**, over which roofs **972** have been grown (for example, by epitaxial lateral overgrowth over silicon dioxide that was later removed), such that the leading edge of each roof **972** extends to or slightly over the opposite sidewall **973** (thus giving the appearance of the structure an impression of a baseball stadium dugout).

FIG. **9**L is a perspective-view schematic diagram of a side-flow dugout substrate **982** on which has been grown a nanotube forest **89**. The roofs **973** and the remaining top surface **974** together form a growing surface that allows growth of nanotube forest **89** on a substantially continuous basis in the X and Y directions, wherein the reactant gas flows through channels **971**, then permeates up and out of the dugout to feed the growth of nanotube forest **89** at its base. This allows even the interior of forest **89** to be fed with a sufficient supply of reactant so all the nanotubes grow at the same rate.

FIGS. **9**M, **9**N, and **9**O are perspective-view schematic diagrams of making a substrate **977** into a side-flow or through-flow substrate **985** for growing carbon nanotube forests **89**, according to some embodiments.

FIG. **9**M shows a substrate **977** after having channels **975** that have been etched using DRIE in order to form wide-bottomed channels **976**, in some embodiments, for example, as described in U.S. Pat. No. 6,127,273 mentioned above.

FIG. **9**N shows substrate **977** after having added epitaxial growth **987** that substantially closes the tops of channels, while leaving the wide channel bottoms substantially open.

FIG. **9**O shows substrate **977** after having anodic nanoporous etching, as described above. In some embodiments, the anodic nanoporous etching forms micropores and nanopores **988** into the top layer **987**, such that reactant gas can flow through channels **976** and the micropores and nanopores in order to supply nanotube growth in the interior portion of growing nanotube forest **89**.

FIG. **10**A is a perspective schematic diagram of apparatus **1000** and method for making a continuous-web carbon nanotube film structure **1093**. In a manner similar to that shown in FIG. **2**D, criss-crossed lengths of carbon nanotube film **1098** are laid across film-holding belts **1037** and **1038**, which, in some embodiments, are at least partially coated with pressure-sensitive adhesive. In some embodiments, one or more spools **652** (e.g., from an apparatus such as shown in FIG. **6**A) dispenses nanotube film **1098**, which is laid across the span between holding belts **1037** and **1038**, pulled sufficiently tight for the desired resulting structure **1093**, and then attached to holding belt **1037** and holding belt **1038**. E.g., in some embodiments, a non-stick bar **1011** is used to press film **1098** into the adhesive on belt **1037** when it reaches that side, and non-stick bar **1012** is used to press film **1098** into the adhesive on belt **1038** when it reaches the opposite side. Illustrated schematically in FIG. **10**A, the films **1098** are dispensed at an angle to the direction of movement of structure **1093** (e.g., at 10 to 80 degrees to the direction of movement **1030**. In some embodiments, belts **1038** and **1039** are continuous-loop belts that run as a conveyor around pulleys **1039**. In some embodiments, the completed structure **1093** is a continuous web that is transferred to sheet holder belt **1050** for further processing downstream (to the right). In some embodiments, sheet holder belt **1050** includes a flexible sheet **1055** having adhesive strips **1057** and **1058** along opposite edges.

In other embodiments, as described below for FIG. **10**E, sheet holder belt **1050** instead includes a microporous surface through which air is pulled (e.g., from a vacuum applied through a smooth perforated support surface **1061** underneath sheet holder belt **1050**) in order to hold structure **1093** sheet holder belt **1050** without adhesive strips **1037** and **1038**. This has the advantage of being able to reverse the air flow to provide a pressure (rather than vacuum) in order to easily release the assembled criss-cross film structure **1093** from sheet holder belt **1050** as desired.

In some embodiments, a plurality of films **1098** (e.g., A, B, and C shown here) are laid side-by-side, back and forth, edge-to-edge, across the build area as the conveyor mechanism moves in direction **1030**.

In some embodiments, belts **1037** and **1038** are omitted, and the films **1098** are assembled in a like manner directly onto sheet holder belt **1050** (e.g., using non-stick bars **1011** and **1012** being used to press the taut film into adhesive strips **1057** and **1058**). In other embodiments, sheet holder belt **1050** instead includes the microporous surface through which a vacuum is pulled as described above. This has the advantage of directly laying and holding the films **1098** with vacuum to hold the films, and then being able to reverse the air flow to provide a pressure (rather than vacuum) in order to easily release the assembled criss-cross film structure **1093**.

FIG. **10**B is a cross-section view schematic diagram of a transfer step in making a continuous-web carbon nanotube film structure **1093**. In this view, holder belts **1038** and **1037** are moving towards the viewer outside the edges of sheet **1055** on which adhesive strips **1058** and **1057** are affixed. Other embodiments use vacuum attachment to a microporous sheet member **1050** as just described.

FIG. **10**C is an enlarged perspective schematic diagram of a transfer step in making a continuous-web carbon nanotube film structure **1093**. In the embodiment shown, non-stick presser rollers **1013** and **1014** press crossed-film structure **1093** onto conveyor **1050**, thus removing crossed-film structure **1093** from belts **1038** and **1037**. In some embodiments, presser rollers **1013** and **1014** also include a cutting edge **1015** to help cut crossed-film structure **1093** from belts **1038** and **1037**.

FIG. **10**D is a top-view schematic diagram of the transfer step described in FIG. **10**C.

FIG. **10**E is a perspective schematic diagram of system **1005** showing assembly and densification steps in making a densified continuous-web carbon nanotube film structure **1094**. In some embodiments, a continuous-loop microporous plastic sheet **1056** is passed across perforated vacuum table **1061**, and air **1062** is pulled through microporous plastic sheet **1056** to hold a cross-cross pattern of nanotube films **1098** as it is formed into crossed-film structure **1093** as described above. (In other embodiments, continuous adhesive strips **1058** along the edges of sheet **1055** such as shown in FIG. **10**B are used.) In some embodiments, belt **1056** and the as-laid (undensified) continuous-web nanotube film structure **1094** on its surface are then dipped into a liquid bath **1066**, such as ethanol, for example, and then withdrawn vertically and dried using air **1065** to densify the carbon-film that is drawn thinner with the shrinking and thinning liquid film on the surface of sheet holder belt **1050**. In some embodiments, once the densified film is dry (e.g., at the top of FIG. **10**E), air pressure is applied through the microporous plastic sheet **1056**, in order to separate the densified film **1094** from microporous plastic sheet **1056** in a continuous web for later processing or spooling onto a take-up reel.

FIGS. **11**A-**11**F are perspective schematic diagrams of steps in making a continuous web of crossed films, where each film in the assembly is being held at its ends by a first and second adhesive member of a conveying mechanism that is moved in a rotary rocking motion, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web.

FIG. **11**A is a perspective-view schematic diagram of system **1100** that includes endless-belt adhesive holder **1137** and endless-belt adhesive holder **1138** each moving diagonally downward at an angle ALPHA such that film **1198**, which is being dispensed from spool **652**, travels substantially straight down in direction **1190**. This forms a crossed-film structure **1193** having crossed films at angle two times alpha. In some embodiments, a non-stick bar **1111** is used to press film **1198** into the adhesive on belt **1038** from the left when it reaches that side, and non-stick bar **1112** is used to press film **1198** into the adhesive on belt **1037** from the left. Once film **1198** is attached to belts **1137** and **1138**, the conveying mechanism **1139** is swung (e.g., in the embodiment shown, clockwise) in direction **1151**.

FIG. **11A1** is a side-view of system **1100** as shown in FIG. **11**A.

FIG. **11**B is a perspective-view of system **1100** while the conveying mechanism **1139** is in the midst of swinging in direction **1151**. In some embodiments, conveying mechanism **1139** continues to maintain angle ALPHA.

FIG. **11B1** is a side-view of system **1100** as shown in FIG. **11**B.

FIG. **11**C is a perspective-view of system **1100** after the conveying mechanism **1139** has completed swinging in direction **1151**. In some embodiments, a non-stick bar **1113** is used to press film **1198** into the adhesive on belt **1037** from the right when it reaches that side. In some embodiments, conveying mechanism **1139** continues to maintain angle ALPHA, and is swung in direction **1152** once the film has attached to adhesive member **1137**.

FIG. **11C1** is a side-view of system **1100** as shown in FIG. **11**C.

FIG. **11**D is a perspective-view of system **1100** while the conveying mechanism **1139** is in the midst of swinging back (counterclockwise) in direction **1152**. In some embodiments, conveying mechanism **1139** continues to maintain angle ALPHA.

FIG. **11D1** is a side-view of system **1100** as shown in FIG. **11**D.

FIG. **11**E is a perspective-view of system **1100** after the conveying mechanism **1139** has completed swinging in direction **1151**. In some embodiments, a non-stick bar **1113** is used to press film **1198** into the adhesive on belt **1037** from the right when it reaches that side. In some embodiments, conveying mechanism **1139** continues to maintain angle ALPHA, and is swung in direction **1152** once the film has attached to adhesive member **1137**.

FIG. **11E1** is a side-view of system **1100** as shown in FIG. **11**E.

FIG. **11**F is a perspective-view of system **1100** while the conveying mechanism **1139** is in the midst of swinging in direction **1151**. In some embodiments, conveying mechanism **1139** continues to maintain angle ALPHA. Film structure **1193** now has three layers of film strips, and can continue indefinitely to form a continuous web. In some embodiments, once the end of film **1198** on a first spool is reached, it is spliced (in some embodiments, for example, using the technique described below for FIG. **14**E) to the beginning of a film **1198** on a second spool.

FIG. **11F1** is a side-view of system **1100** as shown in FIG. **11**F.

FIG. **12**A is a perspective schematic diagram of system **1200** showing steps in making a continuous web of crossed films, where each film in the assembly is being held at its ends by a first and second adhesive member of a conveying mechanism, in order to obtain a crossed-film structure of a plurality of carbon-nanotube films in a continuous web. In some embodiments, system **1200** that includes endless-belt adhesive holder **1237** and endless-belt adhesive holder **1238** (in some embodiments, each having an adhesive coating **115**) moving downward at an angle ALPHA such that film **1198**, which is being dispensed from spool **652**, travels substantially straight down in direction **1190**. The film **1198** here is dispensed to stick to moving conveyor **1239**, which, in some embodiments, includes flexible adhesive belts **1237** and **1238**. In some embodiments, the lower ends of belts **1237** and **1238** are positioned as defined by fixed horizontal axle **1217**, while the upper ends of belts **1237** and **1238** are twisted to follow axle **1216**, which is swung back and forth as in FIGS. **11**A-**11**F above. This allows the final end of conveying mechanism **1239** to remain fixed relative to machinery further downstream.

FIG. **13**A is a perspective schematic diagram of a system **1300** that shows a method for making a plurality of continuous yarns from a plurality of carbon-nanotube films pulled from carbon-nanotube forests. In some embodiments, system **1300** includes a plurality of film-holding bars **1399** pulling a film **99** from the face **86** of a carbon-nanotube forest **89**, each using a rounded-front adhesive bar **1318**. In other embodiments, other non-adhesive methods, such as described elsewhere herein are used to affix the leading ends of the films to film-holding bars **1399**. In some embodiments, every other one of the film-holding bar **1399** (e.g., the even-numbered second and fourth film-holding bars **1399** in the diagram) are initially extended further (to the left, in the negative X direction in the diagram) in order to start their pull first, and in order to move further right with their film pull than the odd-numbered film-holding bars **1399**, in order that they can spin without interfering with one another. Once sufficient film **99** has been initially pulled, rods **1319** will start to spin, to create a plurality of nanotube yarns similar to the single yarn described in the Zhang et al. 2004 article referred to above. In some embodiments, each film-holding bar **1399** includes a reference surface **1316** that is configured to rest on surface **79** of substrate **77**, in order that the rounded front adhesive surface **1318** engages face **86** of nanotube forest **89** at a height (e.g., the middle) suitable to start a film pull. In some embodiments, the height is empirically determined. In some embodiments, a slight vertical motion is imparted as adhesive surface **1318** engages face **86** of nanotube forest **89** to get better contact for starting the film pull.

FIG. **13**B is a perspective schematic diagram of system **1300** after spinning **1351** of each rod **1319** has started, making the plurality of continuous yarns **1398** from the plurality of carbon-nanotube films **1311** pulled from carbon-nanotube forest **89**. In some embodiments, once the initial nanotube forest **89** has been harvested and spun into yarns **1398**, carbon nanotubes from another forest **89'** (or from a film **98** formed as described above) are spliced to the tail end(s) of the films **1311** pulled from the initial nanotube forest **89**. In some embodiments, the spinning **1351** of each rod **1319** is stopped first, in order to pull more film **99** for the splicing process **1303**.

FIG. **13**C is a perspective schematic diagram of a splice process **1303** in which a first carbon nanotube film **99** (or the individual portions **1311** of that film) being pulled from a first carbon nanotube forest **89** is about to be spliced to a second carbon nanotube forest **89'** using splicer bar **130**, in a manner similar to that described above for FIGS. **1**R-**1**T. In some embodiments, splicer bar **130** includes a non-adhesive front nose **141** configured to press film **99** into approximately the center of front face **86'** of forest **89'**. In some embodiments, front nose **141** includes a porous front surface (see FIG. **14**A) through which a vacuum is selectively applied in order to hold and later release film **99** during the splice process **1303**. Some embodiments of splice bar **130** also include a cutting edge **142** for severing the initial film **99** once the splice has been made.

FIG. **13**D is a perspective schematic diagram of carbon nanotube yarns **1398** being pulled from nanotube films **1311** the second carbon nanotube forest **89'** after being spliced and removed from the first carbon nanotube forest **89**. Splicer bar **130** is being withdrawn. In some embodiments, substrate **77'** is swung in direction **1351** back to a normal pulling position. In this manner a plurality of continuous yarns **1398** are continuously pulled from a successively presented plurality of carbon-nanotube forests **89** from different substrates **77**.

FIG. **14**A is a perspective schematic diagram of a system **1400** for in initiating and pulling a continuous nanotube film **99** from a carbon-nanotube forest **89** using a vacuum film-holding bar **1499**. In some embodiments, vacuum film-holding bar **1499** includes one or more internal channels **1417** leading to a microporous front interface, e.g., made of porous ceramic having a composition similar to the ceramic filters described in U.S. Pat. No. 6,394,281 by Ritland et al., which is incorporated herein by reference.

FIG. **14**B is a perspective schematic diagram of system **1400** with a vacuum film-holding bar **1499** pulling nanotube film **99** from carbon-nanotube forest **89**.

FIG. **14**C is a perspective schematic diagram of system **1402** useful for transferring films **98** obtained by pulling a continuous film **99** from a carbon-nanotube forest **89** using vacuum film-holding bar **1499**, in a manner similar to that shown in FIGS. **1**J and **1**K. In some embodiments, each of vacuum film-holding bars **1431**, **1432**, and **1433** are of a construction substantially similar to vacuum film-holding bar **1499**. The use of vacuum film-holding bars allows a vacuum/air suction to be applied at a time when adhesion or holding of the film is desired, and then for air pressure to be applied at a later time when release of the film is desired. In some embodiments, vacuum film-holding bar **1431** is omitted, and vacuum film-holding bar **1499** serves that purpose.

FIG. **14**D is a perspective schematic diagram of system **1402** after transferring film **98** to vacuum film-holding bars **1431** and **1432** and separating it from continuous film **99** that continues to be pulled from carbon-nanotube forest **89** using vacuum film-holding bar **1433**.

FIG. **14**E is a perspective schematic diagram of splicing films **99** and **99'** while pulling a continuous film **99** from carbon-nanotube forests **89** and **89'** from different substrates **77** and **77'** using vacuum film-holding bars **1499** and **1499'**. In some embodiments, film **99** is being pulled from front face **86** of forest **89** using vacuum film-holding bar **1499**. The harvest of nanotube forest **89** is nearly complete. New film **99'** is pulled from front face **86'** of forest **89'** using vacuum film-holding bar **1499'**. Film **99** is moved into contact with new film **99'** using vacuum film-holding bar **1499**, which, after sufficient contact has spliced film **99** to film **99'**, then applies air pressure to release the films from vacuum film-holding bar **1499**. In some embodiments, a cutting or tearing operation severs the remaining tail of film **99** from the sliced film.

FIGS. **15**A, **15**B, **15**C, **15**D, and **15**E are top-view schematic diagrams of system **1500** building a cross-woven nanotube cloth **1593** on a vacuum table **1561**. FIG. **15**A shows system **1500** after laying nanotube film strip **1511** and holding it by vacuum to table **1561**. In some embodiments, nanotube film **99** is directly pulled from nanotube forest **89** that was grown on substrate **77**, and is laid on vacuum table **1561** to form strip **1511**. Upon reaching an edge (the bottom edge in the diagram) of the vacuum surface **1562**, substrate **77** is raised and inverted at an angle of reflection equal to the angle of incidence. FIG. **15**B shows system **1500** in state **1502** after laying second nanotube film strip **1512** and holding it by vacuum to table **1561**. Upon reaching the next edge (the left edge in the diagram) of the vacuum surface **1562**, substrate **77** is again raised and un-inverted at an angle of reflection equal to the angle of incidence. FIG. **15**C shows system **1500** in state **1503** after laying third nanotube film strip **1513** and holding it by vacuum to table **1561**. Upon reaching the next edge (the top edge in the diagram) of the vacuum surface **1562**, substrate **77** is raised and again inverted at an angle of reflection equal to the angle of incidence. FIG. **15**D shows system **1500** in state **1504** after laying fourth nanotube film strip **1514** and holding it by vacuum to table **1564**. FIG. **15**E shows system **1500** in state **1505** after laying fifth nanotube film strip **1515** and many more and holding them by vacuum to table **1564**.

FIG. **15**F is a side view partially in cross section of system **1500** in state **1505**, showing an air-flow connection **1564** for selectively applying either vacuum (to attach and hold nanotube film **99** to surface **1562** of substrate **1561** for formation of film structure **1593** and/or for further processing such as coating film structure **1593** with a liquid such as ethanol which is then evaporated to thin and densify film structure **1593**, or for impregnating film structure **1593** with a binder such as PVA, epoxy, and/or the like) or air pressure (to release the completed film structure **1593** from its surface). In some embodiments, substrate **1561** includes a plurality of interior passages **1563** coupled between air-flow connection **1564** and a microporous surface layer **1562** (e.g., in some embodiments, for example, having an inner structure and composition similar to the ceramic filters described in U.S. Pat. No. 6,394,281 mentioned above, or in other embodiments, substrate **1561** is a flow-through (e.g., silicon) wafer such as described in FIG. **8**K, FIG. **9**J or FIG. **9**N) through which the vacuum or air pressure are applied. In some embodiments, film **99** is applied directly as it is pulled from nanotube forest **89** on substrate **77**, while in other embodiments, a preformed film **98** (as described in any of the embodiments above) is applied to surface **1562**. In some embodiments, the vacuum holds a plurality of stacked film layers because each film is essentially an aerogel-type material through which air can readily pass. In some embodiments, the microporous top layer has through openings small enough that the sideways-oriented nanotubes are not sucked into its surface, but rather lie across it until released by a reverse of the air flow or pressure. In some embodiments, top surface **1562** is an essentially flat plane; while in other embodiments, the top surface has a three-dimensional shape in the form of the desired end product, used as a mold.

FIGS. **16**A and **16**B are perspective schematic diagrams of system **1600** building a cross-woven nanotube airfoil **1693** using a continuous web of crossed films **98**, where each film **98** in the assembly is being held across its entire length and width by a curved vacuum table **1677**. In some embodiments, film **99** is applied directly as it is pulled from nanotube forest **89** on substrate **77**, while in other embodiments, a preformed film **98** (as described in any of the embodiments above) is applied to surface **1562**. In some embodiments, film structure **1593** is coated with a liquid such as ethanol (e.g., by spraying a mist or dipping into the liquid), which is then evaporated to thin and densify film structure **1593**. In some embodiments, once the film structure **1693** is completed, a binder of, e.g., PVA, epoxy, or the like is applied.

Various embodiments of the invention include combinations of subsets of features from a plurality of embodiments described herein, and are specifically contemplated by the inventor.

In some embodiments, adhesive strips and/or adhesive-coated rods are used in conjunction to create a layered and flattened nanotube structure. In such an embodiment, an adhesive strip of an appropriate width is used to draw a nanotube sheet. Once drawn with the adhesive strip, the end of the nanotube sheet to which the adhesive strip is attached is, in turn, attached to a second adhesive-coated rod, and the adhesive strip is removed. This nanotube sheet is attached by folding the end of the nanotube sheet over the second rod, such that the rod is connected to the nanotube sheet. In some embodiments, these adhesive-coated rods are 1 to 2 mm in diameter and of some suitable length corresponding to the width of the nanotube-forest-bearing substrate. In some of the various embodiments, these "rods" are made from steel, iron, aluminum, plastic, rubber, rubber-coated steel cable, or some other suitable material.

In some embodiments, once the second adhesive-coated rod is employed, a first adhesive-coated rod is placed at the first end of the nanotube sheet. The first and second adhesive-coated rods are used in combination to manipulate an individual nanotube sheet. In some embodiments, the first and second adhesive-coated rods are used to manipulate and/or transfer a nanotube sheet to a second set of rods comprising a third and fourth adhesive-coated rods. Using the adhesive strips and the first and second adhesive-coated rods to transfer a nanotube sheet, a layered nanotube structure can be built up, whereby the process of generating nanotube sheets is repeated, as is the transfer of these sheets from the adhesive-strip holder to the first and second rods, and finally to the third and fourth rods. Specifically, several nanotube sheets are layered one on top of another, with the ends of the nanotube sheets attached to the adhesive-coated third and fourth rods.

In at least one embodiment, once a nanotube structure of a suitable thickness is created through the layering of the nanotube sheets, the third and fourth adhesive-coated rods are rotated in opposite directions (i.e., one in a clockwise and another in a counter-clockwise direction) to flatten the layers that comprise the nanotube structure.

In some embodiments, once a series of nanotube structures are created, they are combined to generate a cross-hatch or cross-layer pattern. These cross-hatch or cross-layer patterns and the size of the nanotube structures generated in a cross-match or cross-layer pattern are only limited by the number of the nanotube structures used. Once the requisite cross-hatch or cross-layer patterns is formed, the third and fourth adhesive rods used to manipulate each individual nanotube structure are removed, leaving a complete nanotube structure formed in a cross-layer or cross-hatch pattern.

The process of generating a structure or fabric using a loom is well known. U.S. Pat. No. 169 (by Erastus B. Bigelow, issued Apr. 20, 1837), which is incorporated herein in its entirety, describes a power-loom for weaving coach lace and other similar fabrics. Common to most looms is the use of warp threads, weft threads, and a space between the warp threads called a shed. Typically, the process of weaving fabrics using a loom includes alternately raising and lowering a series of warp threads oriented to each other in a generally parallel manner, such that one set of parallel warp threads would be raised, and an adjacent set of parallel warp threads would be lowered. In some embodiments, each thread of the second set is located between two threads of the first set. Between each alternate raising and lowering of these sets of warp threads, a weft thread is passed through the space (or "shed") between the sets of warp threads. Looms automate this process of raising, lowering and the passing through of weft threads to create fabrics.

In at least one embodiment, modifications of traditional weaving techniques utilizing a loom, such as disclosed in U.S. Pat. No. 169, are used to form a single nanotube structure consisting of multiple smaller structures of nanotubes. In such an embodiment, a set "A" of layered, condensed nanotube structures are attached to a loom. A second set "B" of layered, condensed nanotube structures is also attached to a loom. Collectively, set A and set B are referred to as warp films and individually as a warp film. In some embodiments, set A and set B are spread out in a horizontal array (i.e., a horizontal loom) while in other embodiments, a vertical array (i.e., a vertical loom) is used. In some embodiments, the distance or "shed" between the outer-most A and B warp films is greater than the distance between other warp films in the set A or B as attached to a loom, such as described in FIGS. **2**E and **2**F. In some embodiments, the shed is the same between all warp-film sets as described in FIG. **2**C. In some embodiments, when a loom containing sets A and B is operated, the nanotube structures of set B are placed in an up position, while the nanotube structures of set A are placed in a down position. Once the loom is operated to place a weft structure, the positions of sets A and B alternate. While sets A and B alternate, a series of additional nanotube structures serve as wefts and are passed into the shed existing between the members of set A and set B. These wefts are thus, in effect, woven into the warps forming set A and B. In some embodiments, the wefts are shifted toward the point at which the warp sets are attached so as to strengthen the woven nanotube structure. Once this process is competed, a woven nanotube structure is created.

In some embodiments, a combination of adhesive-coated rods and rollers are utilized to draw nanotube sheets from one or more nanotube forests attached to one or more substrates. In some embodiments, the substrate is formed from a glass, silicon (Si) or sapphire, and, in some embodiments, is between 1 and 50 cm wide or wider. In some embodiments, the substrate has a porous surface, wherein in some embodiments, the surface pores are about 10 nanometers or smaller across. In some embodiments, the height of the forest of nanotubes is grown to approximately 0.25 mm. This height can be varied based upon the process used to form the nanotube fibers as is described above. In one embodiment, one or more nanotube sheets are drawn, pulled together to form multiple layers, and flattened using a series of rollers. Once flattened, in some embodiments, a PVA (poly(vinyl alcohol)) solution or some other suitable solution is sprayed onto the newly formed nanotube structure in order to densify the structure. Specifically, the effect of the liquid evaporating is to shrink the nanotube sheet, thus making the sheets themselves denser. In some embodiments, a PVA (poly(vinyl alcohol)), ethanol or some other suitable liquid bath is used whereby the nanotube structure is passed through the bath to allow for the nanotube structure to densify. After being passed through the bath, the nanotube structure is passed around a rotating drum, allowed to dry, and accumulated in a roll. In some embodiments, strips of the nanotube structure are cut at a predetermined length, and spliced together to form a long continuous piece of layered, flattened nanotube film.

Some embodiments of the invention provide a nanotube article that includes a plurality of nanotube films stacked on a continuous web in each of one or more directions relative to a length-wise edge having the longest dimension of the web. In some embodiments, the web is densified and wound on a take-up roll. In some embodiments, the web and each of the plurality of nanotube films includes carbon fullerene nanotubes. In some embodiments, the web includes woven nanotube films. In some embodiments, the web includes a first set having a plurality of nanotube warp films positioned at a first angle to a length-wise edge of the web woven with a second set having a plurality of nanotube weft films positioned at a second angle, different than the first angle, to a length-wise edge of the web. In some embodiments, the web includes crossed-but-not-woven nanotube films. In some embodiments, the web includes a first set having a plurality of nanotube films parallel to one another crossed-but-not-woven with a second set having a plurality of nanotube films parallel to one another.

Another aspect of the invention, in some embodiments, includes an apparatus for continuous fabrication of a carbon nanotube film, wherein the apparatus includes a first film-transport mechanism having one or more nanotube-film-holding surfaces, and movable along a first fabrication path; and a layer-build-up mechanism operable to place carbon nanotube film across the nanotube-film-holding surfaces while the holding surfaces are moving along the fabrication path. In some embodiments, the nanotube-film-holding surfaces include one or more adhesive surfaces along a surface of a flexible sheet belt, wherein the layer-build-up mechanism lays each film at a non-parallel non-perpendicular angle to a lengthwise edge of the sheet belt. In some embodiments, the belt is a continuous-loop made of a polymer material having the adhesive surfaces along its two opposite outer edges, and wherein the nanotube film is placed across the belt and held by the one or more adhesive surfaces. In some embodiments, the nanotube-film-holding surfaces include one or more adhesive surfaces along a surface of each of a plurality of separate spaced-apart endless-loop belts moved substantially piecewise parallel to one another. Some embodiments further include a second film transport mechanism having a plurality of spaced-apart adhesive surfaces on a sheet belt, and movable along a second fabrication path that connects to the first fabrication path in a manner to allow transfer of the nanotube film from the first film transport mechanism to the second film transport mechanism. In some such embodiments, the layer-build-up mechanism includes a first set of one or more warp-film holders operable to hold a first set of warp films stretched to a first adhesive strip along a distal first edge of the first film-transport mechanism from the first set warp-film holders, and a second set of warp film holders operable to hold a second set of warp films stretched to the first adhesive strip, wherein the first film-transport mechanism includes a second adhesive strip along a second edge opposite the first edge, and a weft-film placement mechanism operable to place a weft film in a shed between the first set of warp films and the second set of warp films and attach opposite ends of the weft to the first and second adhesive strips respectively and then separate from the attached weft. In some such embodiments, the first set warp-film holders moves in a direction opposite relative to the second set warp-film holders after deposition of a weft film placed from the first adhesive strip to the second adhesive strip, and wherein the warp-film holders successively attach a near end of each warp film to the second adhesive strip as it completes its weave and then separate from the attached warp. In other embodiments, the first film-transport mechanism includes a vacuum table, wherein the nanotube-film-holding surfaces are operable to hold and release nanotube film using a gas-pressure difference, the vacuum surface movable relative to layer-build-up mechanism to position itself for a predetermined film deposition layout.

Another aspect of the invention, in some embodiments, includes an apparatus on which to synthesize a carbon nanotube forest, wherein the apparatus includes an interior-flow substrate having a first major face, a first nanoporous surface layer in fluid communication with the first major face, an interior flow system operable to deliver gasses to the nanoporous layer from a side or face of the substrate other than the first major face, and a nanotube-synthesis catalyst on the first nanoporous layer. In some embodiments, the interior flow system includes a first plurality of gas passages having a depth greater than their width. In some embodiments, the substrate is a side-flow substrate wherein each one the first plurality of gas passages provide fluid communication to the porous layer from one or more sides adjacent the first major face. In some embodiments, the interior flow system includes a first plurality of gas passages having a depth greater than their width and having a length along a Y-direction, and a second plurality of gas passages that extend to a depth more distal from the first major face than the depth of the first plurality of gas passages, and wherein each of the second gas passages is in fluid communication with a plurality of the first plurality of gas passages, in order to form a flow-through substrate. Some embodiments further include a furnace having a temperature control and heating unit operable to maintain an effective temperature for nanotube synthesis; a substrate-holding mechanism; a gas-flow system operable to deliver one or more reactant gasses to a side or face of the substrate other than the first major face and to exhaust spent gasses from a vicinity of the first major face; and an access port through which nanotube product can be removed without interrupting a substantially continuous operation of the furnace at substantially its effective temperature for nanotube synthesis. In some such embodiments, the substrate is configured to have plurality of successive nanotube forests grown and harvested.

Some embodiments of the invention provide a method that includes stacking a plurality of nanotube films on a continuous web in each of one or more directions relative to a length-wise edge having the longest dimension of the web. In some embodiments, the method further includes densifying the web and winding it on a take-up roll. In some embodiments, the web and each of the plurality of nanotube films includes carbon fullerene nanotubes. In some embodiments, the method further includes weaving nanotube films to form the web. In some embodiments, the method further includes positioning and holding a first set having a plurality of nanotube warp films at a first angle to a length-wise edge of the web, and weaving the first set with a second set having a plurality of nanotube weft films positioned at a second angle, different than the first angle, to a length-wise edge of the web. In some embodiments, the method includes crossing-but-not-weaving the nanotube films. In some such embodiments, the web includes a first set having a plurality of nanotube films parallel to one another crossed-but-not-woven with a second set having a plurality of nanotube films parallel to one another.

Another aspect of the invention, in some embodiments, includes method for continuous fabrication of a carbon nanotube film, wherein the method includes moving a first film-transport mechanism, having one or more nanotube-film-holding surfaces, along a first fabrication path; and placing carbon nanotube film across the nanotube-film-holding surfaces while the holding surfaces are moving along the fabrication path. In some embodiments, the nanotube-film-holding surfaces include one or more adhesive surfaces along a surface of a flexible sheet belt, wherein the layer-build-up mechanism lays each film at a non-parallel non-perpendicular angle to a lengthwise edge of the sheet belt. In some embodiments, the belt is a continuous-loop made of a polymer material having the adhesive surfaces along its two opposite outer edges, and wherein the method includes placing the nanotube film across the belt and holding it by the one or more adhesive surfaces. In some embodiments, the method performs one or more processes associated with the individual features of the above described apparatus.

Another aspect of the invention, in some embodiments, includes a method for synthesizing a carbon nanotube forest, wherein the method includes flowing reactant gasses to an interior of a nanotube-growth substrate having a first major face, a first nanoporous surface layer in fluid communication with the first major face, an interior flow system operable to deliver gasses to the nanoporous layer from a side or face of the substrate other than the first major face, and a nanotube-synthesis catalyst on the first nanoporous layer. In some embodiments, the interior flow system includes a first plurality of gas passages having a depth greater than their width. In some embodiments, the substrate is a side-flow substrate wherein each one the first plurality of gas passages provide fluid communication to the porous layer from one or more sides adjacent the first major face. In some embodiments, the interior flow system includes a first plurality of gas passages having a depth greater than their width and having a length along a Y-direction, and a second plurality of gas passages that extend to a depth more distal from the first major face than the depth of the first plurality of gas passages, and wherein each of the second gas passages is in fluid communication with a plurality of the first plurality of gas passages, in order to form a flow-through substrate. Some embodiments further include a furnace having a temperature control and heating unit operable to maintain an effective temperature for nanotube synthesis; a substrate-holding mechanism; a gas-flow system operable to deliver one or more reactant gasses to a side or face of the substrate other than the first major face and to exhaust spent gasses from a vicinity of the first major face; and an access port through which nanotube product can be removed without interrupting a substantially continuous operation of the furnace at substantially its effective temperature for nanotube synthesis. In some such embodiments, the substrate is configured to have plurality of successive nanotube forests grown and harvested.

Some embodiments provide a method that includes holding a first end of a nanotube film, pulling a length of nanotube film attached to the first end from a nanotube forest, holding a second end of the nanotube film, and separating the second end of the film from the nanotube forest. In some embodiments, the holding includes adhesively holding. In some embodiments, the holding includes vacuum holding. In some embodiments, holding includes clamping the film between two surfaces. Some embodiments further include holding the film between the second end and the forest before separating.

Some embodiments of the invention include splicing a nanotube film to a nanotube forest and pulling additional length of nanotube film from the nanotube forest. In some embodiments, the splicing includes pressing a nanotube film against the nanotube forest. In other embodiments, the splicing includes pressing a portion of one nanotube film against a portion of another nanotube film. In some embodiments, splicing includes wetting overlapped portions of two or more nanotube films and then drying the wetted films to draw the fibers closer to one another.

Another aspect of the invention, in some embodiments, includes a splicing bar having a rounded nose configured to press a nanotube film onto another nanotube film and/or to a nanotube forest. In some embodiments, the slicing bar further includes a cutting edge configured to cut a film end off the spliced joint.

Another aspect of the invention, in some embodiments, includes a film-holder opener **185** configured to open a split resilient nanotube-film holder, to insert the nanotube film therein and then to release the nanotube-film holder with the nanotube film held therein. In some embodiments, the nanotube-film holder is made of split rubber tubing.

Another aspect of the invention, in some embodiments, includes a method for preventing or repairing gaps in a nanotube film being pulled from a nanotube forest. In some embodiments, the method includes rotating a distal nanotube film holder and a substrate holding the nanotube forest both in the same angular direction as shown in FIG. **3**B. In other embodiments, the method includes pressing a face of the nanotube forest with an implement that reduces a gap in the forest as shown in FIG. **6**C.

Another aspect of the invention, in some embodiments, includes an apparatus for producing a nanotube film that includes a furnace that includes an access port; a reaction chamber positioned within the furnace, and adapted to hold within the reaction chamber a nanotube-growth substrate that includes a nanotube-growth surface on which a nanotube forest can be synthesized; and a pulling bar, wherein the pulling bar is adapted to be contacted to the nanotube forest and to harvest the nanotube forest into a nanotube film separated from the growth surface and withdrawn through the access port of the furnace. Some embodiments further include the nanotube-growth substrate, wherein the substrate is an interior-flow substrate that provides one or more gas channels to an interior portion of the growth surface of the substrate. Some embodiments further include a reactant-gas inlet communicatively coupled to the one or more gas channels. Some embodiments further include an exhaust-gas outlet that directs flow of output gas to exit the furnace. In some embodiments, the reaction chamber suppresses direct flow of input or output gas across an outer surface of the nanotube forest during its growth. Some embodiments further include a nanotube-film splicer. Some embodiments further include one or more baffles that direct reactant gas flow to an interior of the nanotube forest during growth of the nanotube forest. Some embodiments further include one or more baffles that direct output gas flow in a direction substantially parallel to a direction of growth of the nanotube forest. Some embodiments further include a take-up reel operatively coupled to continuously pull a nanotube film through the access port, wherein the nanotube film is pulled from the nanotube forest and wound around the reel. Some embodiments further include a cooling box connected to the access port, wherein the take-up reel is positioned within the cooling box, and wherein a gas pressure difference between a gas pressure in the cooling box and a gas pressure in the furnace controlled to suppress gas flow through the access port.

In some embodiments, the take up reel is adapted to be raised and lowered relative to the substrate to control an angle of the nanotube film relative to the nanotube forest. In some embodiments, the cooling box includes an input gas inlet that is adjustable to control a gas pressure in the cooling box. Some embodiments further include a cooling jacket surrounding the access port. In some embodiments, the nanotube forest includes a plurality of multi-walled carbon-fullerene nanotubes (MWNTs).

Some embodiments include an apparatus for producing a nanotube forest that includes a first nanotube growth substrate having an outer surface configured to grow nanotube forests simultaneously on each of two non-coplanar growth areas. Some embodiments further include a furnace, and at least one reaction chamber positioned within the furnace, wherein the reaction chamber is configured to hold at least one nanotube growth substrate including the first nanotube growth substrate. In some embodiments, the double-sided substrate is a double-sided flow-through substrate. Some embodiments further include an input gas inlet that allows input gas to enter the furnace. Some embodiments further include an output gas outlet that allows output gas to exit the furnace. In some embodiments, the linked-substrate loop passes through the first access port and the second access port positioned on the furnace and the first access port and the second access port positioned on the reaction chamber. Some embodiments further include a first cooling jacket continuously connected with the first access port positioned on the furnace. Some embodiments further include a take up reel that can pull a nanotube film from a nanotube forest synthesized on an individual linked-substrate. Some embodiments further include a pulling bar. Some embodiments further include a second cooling jacket continuously connected with the second access port positioned on the furnace. Some embodiments further include an input gas inlet, or a plurality of input gas inlets. Some embodiments further include baffles that direct output gas flow.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Although numerous characteristics and advantages of various embodiments as described herein have been set forth in the foregoing description, together with details of the structure and function of various embodiments, many other embodiments and changes to details will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein," respectively. Moreover, the terms "first," "second," and "third," etc., are used merely as labels, and are not intended to impose numerical requirements on their objects.

What is claimed is:

1. An apparatus for producing nanotubes, the apparatus comprising:

a furnace;

a reaction chamber positioned within the furnace;

a gas-supply system that supplies a carbon-bearing precursor gas to an interior of the substrate,

a substrate configured to be positioned within the reaction chamber in the furnace, wherein the substrate includes a cylindrical porous growth surface on which a first nanotube forest is grown in a radial direction, wherein the apparatus is configured to supply a carbon-bearing precursor gas through the cylindrical porous growth surface from an interior of the cylindrical substrate to grow the first nanotube forest on the cylindrical growth surface of the substrate while the substrate is positioned in the reaction chamber;

a take-up reel arranged to turn to continuously collect nanotube film from the substrate;

a servo motor arranged to rotate the substrate; and

an optical sensor connected to the servo motor to keep a front edge of nanotube forest at an optimal position and angle for pulling the nanotube film.

2. The apparatus of claim **1**, further comprising:

a cool-chamber box surrounding the take-up reel; and

an access port that connects the reaction chamber to the cool-chamber box; and

a positive-pressure gas inlet that provides gas into the cool-chamber box to maintain a positive pressure within the cool-chamber box.

3. A method for producing nanotubes, the method comprising:

providing a porous substrate positioned within a reaction chamber in a furnace, wherein the substrate includes a cylindrical growth surface on which a first nanotube forest is grown in a radial direction, wherein the apparatus is configured to supply a carbon-bearing precursor gas through the cylindrical porous growth surface from an interior of the cylindrical substrate to grow the first nanotube forest on the cylindrical growth surface of the substrate while the substrate is positioned in the reaction chamber, and wherein the porous substrate includes a porous ceramic having an anodic-etched polysilicon coating that in turn has a metal coating;

supplying a carbon-bearing precursor gas to an interior of the substrate from a gas-supply system;

growing, in a radial direction, a first nanotube forest on the cylindrical growth surface of the substrate; and

removing nanotubes from the substrate, in a tangential direction relative to the cylindrical growth surface, from outside the reaction chamber through an access port while the substrate is in the reaction chamber.

4. The method of claim **3**, wherein the providing of the porous substrate includes:

providing a porous ceramic cylindrical substrate;

coating the porous ceramic cylindrical substrate with polysilicon;

treating the polysilicon coating with an anodic etch in ethanol and hydrofluoric acid to create a nanoporous surface; and

depositing a metal catalyst on the anodic-etched polysilicon.

5. The method of claim **3**, further comprising:

rotating the substrate having the cylindrical growth surface such that a film of the nanotubes from the first nanotube forest is pulled from a leading edge of the nanotube forest that is kept in position as the substrate rotates.

6. The method of claim **3**, wherein the nanotubes are carbon nanotubes, wherein the removing of the nanotubes includes pulling the carbon nanotubes from the first nanotube forest as a film consisting essentially of carbon nanotubes substantially aligned in a first direction.

7. The method of claim **3**, further comprising:

collecting nanotube film from the substrate onto a take-up reel while turning the take-up reel to keep a front edge of nanotube forest at a position such that an acute outward angle for pulling the nanotube film is maintained relative to a tangent to the cylindrical growth surface of the substrate.

8. The method of claim 3, further comprising:

pulling a plurality of nanotube films, wherein each one of the plurality of nanotube films is pulled from a respective nanotube forest; and

stacking the plurality of nanotube films to form the composite nanotube film.

9. The method of claim 8, wherein the pulling of the plurality of nanotube films includes:

adhering a first end of each respective one of the plurality of nanotube films to a respective one of a first plurality of substrates;

adhering a second end of each respective one of the plurality of nanotube films to a respective one of a second plurality of substrates;

stacking the first plurality of substrates on each other and stacking the second plurality of substrates on each other such that the respective plurality of nanotube films are held parallel to one another; and

rotating the stacked first plurality of substrates relative to a plane of the nanotube films such that the plurality of parallel nanotube films are moved into contact with one another.

10. The method of claim 8, wherein the plurality of nanotube films includes:

a first nanotube film consisting essentially of nanotubes pulled as a film from a first nanotube forest, wherein the nanotubes of the first nanotube film are substantially aligned in a first direction, the first direction being not parallel to and at a first angle relative to a length-wise edge of the web; and

a second nanotube film consisting essentially of nanotubes pulled as a film from a second nanotube forest, wherein the nanotubes of the second nanotube film are substantially aligned in a second direction, the second direction being not parallel to and at a second angle relative to the length-wise edge of the web, wherein the second angle is different than the first angle, and wherein nanotubes of the second nanotube film are in direct contact with nanotubes of the first nanotube film.

11. An apparatus for producing nanotubes, the apparatus comprising:

a substrate configured to be positioned within a reaction chamber in a furnace, wherein the substrate includes a cylindrical porous growth surface on which a first nanotube forest is grown in a radial direction, wherein the apparatus is configured to supply a carbon-bearing precursor gas through the cylindrical porous growth surface from an interior of the cylindrical substrate to grow the first nanotube forest on the cylindrical growth surface of the substrate while the substrate is positioned in the reaction chamber, and wherein the substrate includes a porous ceramic having an anodic-etched polysilicon coating that in turn has a coating that includes a metal.

12. The apparatus of claim 11, further comprising:

the furnace;

the reaction chamber positioned within the furnace; and

a gas-supply system that supplies a carbon-bearing precursor gas to an interior of the substrate,

wherein the apparatus is configured to use the carbon-bearing precursor gas to grow the first nanotube forest on the cylindrical growth surface of the substrate while the substrate is positioned in the reaction chamber,

wherein the reaction chamber includes an access port that allows access to the substrate from outside the reaction chamber while the substrate is in the reaction chamber, and

wherein the apparatus removes nanotubes from the first nanotube forest through the access port while the substrate is in the reaction chamber.

13. The apparatus of claim 12, wherein the substrate includes a plurality of interior passageways leading from the gas-supply system to the porous growth surface.

14. The apparatus of claim 12, wherein the substrate includes a plurality of interior passageways leading from the gas-supply system to the porous growth surface, wherein each of the plurality of passageways includes a plurality of successively smaller branches.

15. The apparatus of claim 12, wherein the nanotubes are carbon nanotubes, wherein the apparatus removes the carbon nanotubes from the first nanotube forest as a film that has a length substantially greater than its length, the film consisting essentially of carbon nanotubes substantially aligned in a first direction.

16. The apparatus of claim 12, further comprising a plurality of vanes to direct exhaust gas radially outward from the cylindrical growth surface.

17. The apparatus of claim 12, further comprising a plurality of exhaust vents to receive exhaust gas outward from the cylindrical growth surface.

18. The apparatus of claim 12, further comprising a take-up reel arranged to turn to continuously collect nanotube film from the substrate that includes the cylindrical porous growth surface.

19. The apparatus of claim 11, further comprising:

means for supplying a carbon-bearing precursor gas to an interior of the substrate from a gas-supply system;

means for growing, in a radial direction, a first nanotube forest on the cylindrical growth surface of the substrate; and

means for removing nanotubes from the substrate from outside the reaction chamber through an access port while the substrate is in the reaction chamber.

20. The apparatus of claim 11, wherein the coating that includes a metal includes iron that is oxidized.

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