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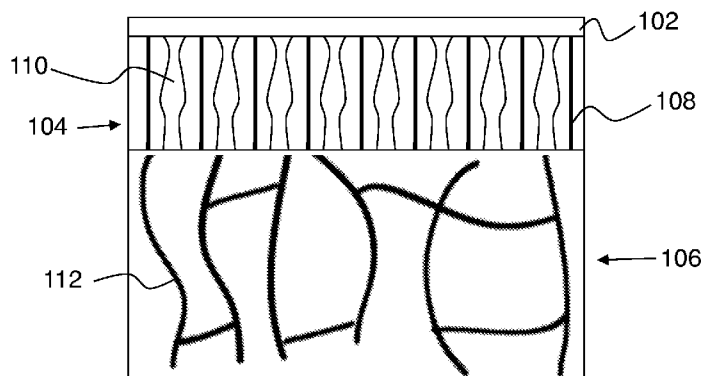


Fig. 1a

(57) Abstract: Membranes for fluid separation are disclosed. These membranes have a matrix layer sandwiched between an active layer and a porous support layer. The matrix layer includes 1-D nanoparticles that are vertically aligned in a porous polymer matrix, and which substantially extend through the matrix layer. The active layer provides species-specific transport, while the support layer provides mechanical support. A matrix layer of this type has favorable surface morphology for forming the active layer. Furthermore, the pores that form in the matrix layer tend to be smaller and more evenly distributed as a result of the presence of aligned 1-D nanoparticles. Improved performance of separation membranes of this type is attributed to these effects.



Membranes having aligned 1-D nanoparticles in a matrix layer for improved fluid separation

FIELD OF THE INVENTION

5 This invention relates to permeable membranes for gas and/or liquid separation.

BACKGROUND

Carbon nanotubes (CNTs) have been considered in connection with permeable membranes for fluid separation
10 for some time. Such membranes often rely on unusual transport properties of fluids through the nanotubes to improve performance. For example, enhanced transport through carbon nanotubes has been considered in US 8,038,887.

15 However, it remains relatively difficult to fabricate permeable membranes having carbon nanotubes (CNTs) as the active material for separation. One significant reason for this is that active layers in permeable membranes are subject to numerous requirements (e.g., reliability,
20 fouling resistance, high flux, good separation capability, etc.) and it can be difficult to meet these requirements with active layers that include carbon nanotubes. Another issue that can arise with such membranes is that CNTs may not provide sufficient separation capability. For example,
25 small ions are difficult to filter out with CNTs.

Accordingly, it would be an advance in the art to provide high-performance separation membranes that are easier to fabricate.

SUMMARY

In this work, we have found that an aligned carbon nanotube mixed matrix membrane with a barrier layer has improved performance. **Fig. 1a** shows an example of this structure. This membrane includes a barrier layer 102 (also referred to as the active layer) that serves to separate solute from solvent. This barrier layer may be for either gas or liquid filtration. Underneath the barrier layer is a matrix layer 104 that includes aligned 1-D nanoparticles (one of which is referenced as 108) in a porous polymer. One of the pores is referenced as 110. The polymer may be any polymer. Underneath matrix layer 104 is a porous support layer 106 that provides additional mechanical support.

We have found, surprisingly, that including matrix layer 104 with its aligned 1-D nanoparticles in a separation membrane (e.g., as shown on **Fig. 1a**) can significantly improve membrane performance. Several factors are believed to contribute to this improved performance. First, this matrix layer appears to provide improved conditions for formation of the barrier layer. Second, this matrix layer appears to provide a pore structure more conducive to increased flow.

For formation of the barrier layer (which can be referred to as the IP layer in some embodiments), the properties of the surface on which it is deposited are important, especially for interfacial polymerization (IP), which is often a preferred approach for fabricating the barrier layer. Preferably, this surface is relatively flat and smooth, with small, evenly distributed pores. We have found that an aligned 1-D nanoparticle matrix layer (e.g., 104 on **Fig. 1a**) can provide such favorable surfaces for formation of the barrier layer. **Figs. 2a-b** show an

example, where **Fig. 2a** is a top view image and **Fig. 2b** is a side view image of a matrix layer 104 including aligned 1-D nanoparticles.

The pores formed within the 1-D nanoparticle matrix layer are smaller in size and are more uniform in distribution as a result of the presence of the aligned 1-D nanoparticles. These differences have been confirmed with SEM analysis. Due to these improved characteristics, flow rate through the membrane can be improved. Pores can be formed in the matrix layer through methods such as phase inversion, drying, or etching. In a phase inversion process, a layer of polymer dissolved in a solvent is immersed in a non-solvent, inducing precipitation of the polymer and the formation of voids within the layer. The structure of the voids is determined by kinetic and thermodynamic factors and is sensitive to concentration, temperature, and additives. The incorporation of aligned 1-D nanoparticles will change the solvent/nonsolvent dynamics and the precipitation of the polymer, resulting in a different structure than would be obtained by phase inversion in a matrix layer not including aligned 1-D nanoparticles. A surprising and noteworthy feature of this improvement of the pores in the matrix layer is that the improvement in flow rate does not depend exclusively on transport through the 1-D nanoparticles. Thus, 1-D nanoparticles other than CNTs can be employed, such as nanofibers, nanorods, etc. If CNTs are employed, they can be either open-ended or close-ended.

The improved membrane performance resulting from 1-D nanoparticles in the matrix layer can be seen by comparing an RO membrane including an aligned CNT matrix layer to a commercial RO Membrane (Filmtec SW30HS). The commercial SW30HS membrane has a measured pure water permeability of 1

lmh/bar, while the aligned CNT membrane with an IP layer has a measured pure water permeability 6 lmh/bar. Both membranes have over 96% rejection and can withstand pressures above 500 psi. This 600% improvement in performance is a result of a superior IP layer that is enabled by the nanotube porous matrix layer.

We also observe that the type, quality, and size of the CNTs influence the performance of the membrane. For smaller nanotubes, where the inner diameter is 2 nm, the pure water permeability is 4 lmh/bar. For larger nanotubes, where the inner diameter is 5 nm, the pure water permeability is 11 lmh/bar. These data show that the incorporation of aligned nanotubes, and the type of nanotube, has a significant influence in the produced porous matrix and the final membrane performance.

Similarly, in forward osmosis membranes with an IP barrier layer, membranes with aligned nanotubes in the matrix layer have improved performance relative to similar membranes without carbon nanotubes. Table 1 below provides some results.

Table 1. Performance data of forward osmosis membrane with a polyamide barrier layer with and without carbon nanotubes in the matrix layer. (Data collected using 1.5 M NaCl draw solution against DI water at room temperature.)

	Measurement	Permeance (LMH)	Reverse Salt Flux (g/L)
FO Membrane without CNTs	Skin to water	35-50	0.05-0.5
"	Skin to draw	60-90	0.05-0.6
FO Membrane with aligned CNTs	Skin to water	42-70	0.2-1.0
"	Skin to draw	80-150	0.1-1.0

Here, LMH is short for "liters per square meter per hour", "skin to water" refers to measurements taken with the barrier layer (i.e., the skin) facing the fresh water side of the separation, while "skin to draw" refers to
5 measurements taken with the barrier layer facing the draw solution side of the separation.

This approach is broadly applicable to any gas or liquid separation, including but not limited to: forward osmosis, reverse osmosis, gas separation, and solute-
10 solvent separation in general. Gas separation applications can be further extended to carbon capture and sequestration.

BRIEF DESCRIPTION OF THE DRAWINGS

15 **Figs. 1a-b** show side and top views of an embodiment of the invention.

Figs. 2a-b show top and side images of a porous matrix layer including aligned 1-D nanoparticles.

20 **Figs. 3a-d** show some alternative embodiments of the invention.

Figs. 4a-h show a first fabrication sequence suitable for making embodiments of the invention.

Figs. 5a-f show a second fabrication sequence suitable for making embodiments of the invention.

25 **Figs. 6a-b** show SEM images relating to the roof layer fabrication approach.

Figs. 7a-b show further SEM images relating to the roof layer fabrication approach.

DETAILED DESCRIPTION

Fig. 1a shows a side view of an embodiment of the invention. **Fig. 1b** shows a corresponding top view of matrix layer 104 by itself. As indicated above, the membrane of **Figs. 1a-b** includes a porous support layer 106, a matrix layer 104, and an active polymer layer 102. Matrix layer 104 is disposed on porous support layer 106 and includes a porous matrix polymer 105 and two or more 1-D nanoparticles disposed in the porous matrix polymer. One of the 1-D nanoparticles is referenced as 108, and one of the pores is referenced as 110. The 1-D nanoparticles are substantially vertically aligned (as shown), and the 1-D nanoparticles substantially extend through matrix layer 104 (also as shown). Active polymer layer 102 and the porous matrix polymer 105 have different compositions. Active layer 102 provides species specific fluid transport. On **Fig. 1a**, the porosity of porous support layer 106 is schematically shown by referencing solid parts of the layer with reference number 112 (i.e., the pores in layer 106 are the spaces between the heavy lines).

Any kind of 1-D nanoparticle can be employed in embodiments of the invention. Here, a 1-D nanoparticle is defined as a particle having at least two of its length (L), width (W) and height (H) being less than one micron, and having an aspect ratio (i.e., $\max(L,W,H)/\min(L,W,H)$) of 10 or more. Suitable nanoparticles include but are not limited to: open-ended carbon nanotubes, close-ended carbon nanotubes, carbon fibers, nanowires, nanorods, and other types of 1-D nano-objects.

Preferably, the thickness of matrix layer 104 is from about 100 nm to about 100 μm . Preferably, the thickness of active layer 102 is from about 0.3 nm to about 500 nm. Any

polymer can be used as matrix polymer 105. Similarly, any material that provides species-specific gas or liquid transport can be used for active layer 102. Suitable materials for matrix polymer 105 include, but are not limited to: cellulose acetate, epoxy, polydimethylsiloxane, polyvinylene fluoride, polysulfone, m- or p- polyaramids. Suitable materials for active layer 102 include, but are not limited to: polyamide, polyethylene glycol (PEG) and its co-polymers.

Active layer 102 can be a gas-selective layer. For example, layer 102 can include poly(amido amine) (PAMAM) or a PEG-nylon block co-polymer, polydimethylsiloxane (PDMS), chitosan, polytrimethylsilyl-1-pentyne (PTMSP), or both to impart the membrane with selectivity to CO₂ or other gases. Alternatively, active layer 102 can be a liquid separation layer for solvent-solute separation. Various applications include, but are not limited to: forward osmosis, reverse osmosis, nanofiltration, pressure retarded osmosis, desalination, carbon capture and/or sequestration, etc.

Figs. 3a-b show embodiments of the invention having anti-fouling layers. The example of **Fig. 3a** shows an anti-fouling layer 304 disposed on active layer 102. The example of **Fig. 3b** shows an anti-fouling layer 304 disposed on porous support layer 106. These approaches can be combined, such that anti-fouling layers are disposed on both active layer 102 and on porous support layer 106.

Figs. 3c-d show embodiments of the invention having further mechanical support in the porous support layer. The example of **Fig. 3c** shows mechanical support 306 embedded in porous support layer 106, while the example of **Fig. 3d** shows mechanical support 106 disposed on a surface of porous support layer 106. Mechanical support 106 can be any structure suitable for providing mechanical support to

porous support layer 106, such as a woven or non-woven mesh or fabric.

One approach for making membranes according to embodiments of the invention is as follows:

5 1) Form vertically aligned 1-D nanoparticles on a substrate;

2) Infiltrate a matrix precursor between the 1-D nanoparticles;

10 3) Form a porous polymer matrix from the matrix precursor to provide a matrix layer including the porous polymer matrix and the vertically aligned 1-D nanoparticles, where the 1-D nanoparticles substantially extend through the matrix layer;

15 4) Form a porous support layer on top of the matrix layer (here, steps 3 and 4 can be performed as two separate steps, or the matrix layer and porous support layer can be formed in a single step);

5) Separate the matrix layer from the substrate; and

20 6) Form an active layer on an exposed surface of the matrix layer, where the active layer provides species-specific fluid transport.

Two refinements of this basic process have also been considered, and are described below in connection with **Figs. 4a-h** and **Figs 5a-f**. The process of **Figs. 4a-h**
25 features the formation of a roof layer to more precisely control the locations of the 1-D nanoparticles during fabrication. This process is especially useful in situations where the 1-D nanoparticles are open-ended nanotubes, because the roof layer facilitates opening the
30 nanotubes during fabrication and protects the nanotubes from plugging by the polymer. The process of **Figs. 5a-f**

features the use of a conformal coating layer on the 1-D nanoparticles. The use of such a conformal coating allows for the use of a wider variety of materials as the matrix polymer precursor.

5 **Fig. 4a** shows aligned 1-D nanoparticles 108 on a substrate 402. Methods for growing aligned 1-D nanoparticles on a substrate are known in the art, and any such method can be employed here.

10 **Fig. 4b** shows the result of depositing a porous roof layer 406 on the 1-D nanoparticles, such that the roof layer and substrate are vertically separated.

15 **Fig. 4c** shows the result of infiltrating a matrix polymer precursor 408 between the 1-D nanoparticles, and also between roof layer 406 and substrate 402. Preferably, matrix polymer precursor 408 is capable of flowing through roof layer 406 in order to facilitate infiltration.

20 **Fig. 4d** shows the result of forming matrix layer 104 from matrix precursor 408. The polymerization is performed such that pores form in layer 104, one of which is referenced as 110. A phase inversion process is a preferred approach for forming matrix layer 104, but any approach for forming a porous layer from precursor 408 can be employed.

25 **Fig. 4e** shows the result of removing roof layer 406. This removal can be performed by any method. In some cases, reactive ion etching or mechanical removal is preferred. Mechanical removal of the roof layer can be helpful in cases where the 1-D nanoparticles are nanotubes, because mechanically removing the ends of nanotubes (as
30 occurs when the roof layer is removed) can be an effective way of ensuring that the nanotubes are open-ended. This step is optional. Infiltration of the matrix precursor can

also form an excess layer above roof layer 406, which forms porous support layer 106 after polymerization. In such cases, matrix layer 104 and porous support layer 106 are formed simultaneously in a single process step, and roof layer 406 remains in the final structure. In the resulting structures, porous roof layer 406 is regarded, by definition, as being part of the porous support layer.

Fig. 4f shows the result of forming porous support layer 106 on matrix layer 104. A phase inversion process is a preferred approach for forming support layer 106, but any approach for forming a porous layer can be employed.

Fig. 4g shows the result of removing substrate 402 from the structure.

Fig. 4h shows the result of depositing active layer 102 on the exposed surface of matrix layer 104. Interfacial polymerization is a preferred approach for forming active layer 102, but any approach for depositing an active layer 102 on matrix layer 104 can be employed.

As indicated above, the process of **Figs. 4a-h** is especially helpful in connection with 1-D nanoparticles that are nanotubes (e.g., carbon nanotubes). In this case, the target of these steps is to infiltrate the space outside of the carbon nanotubes with the matrix polymer, while providing access to the nanotube pore openings on the membrane surfaces. Matrix fill can be achieved by infiltrating (from solution, CVD or PVD) multiple organic materials (e.g., parylene, polymer solvents, in situ polymerization). Further considerations for the process of **Figs. 4a-h** in connection with carbon nanotubes follow below.

One of the challenges in the post-infiltration processing is removing the excess layer on the membrane to

expose the nanotube pores. The process of **Figs. 4a-h** involves several key steps. First, before infiltrating the polymer, the carbon nanotube array gets covered with a roof layer 406 that keeps the nanotubes together during the pre-crosslinking processing steps. The main function of this roof layer, as described below, is to enable mechanical removing of the polymer solution from the top of the CNT array. Mechanical removal of the excess polymer layer is important for obtaining the matrix layer of a desired thickness or structure.

For good infiltration it is very important to achieve a highly porous roof layer, which can be either achieved by tuning the deposition conditions, or by post-deposition etching of the roof layer, or by post-deposition mechanical polishing of this layer. This roof layer on top of the CNT array can be made using CVD coated polymers (parylene), thin layer of graphite or other PVD deposited materials (silica, silicon nitride, gold, etc.).

For effective infiltration, the polymer precursor 408 should have low viscosity to fill the gaps between nanotubes. The easiest way to achieve the fill is to use in situ polymerization or crosslinking of polymers (PDMS, polystyrene, various epoxies). In this step low viscosity precursors 408 are added during infiltration step, the excess is mechanically removed from the membrane surface, and final crosslinking is performed after removal of polymer excess. Example 2 below gives a protocol for CNT membrane fabrication with PDMS polymeric fill.

After the polymer precursor 408 is cross-linked to form matrix layer 104 (using elevated temperature, UV or UV-Vis irradiation, etc.) the roof can be removed using plasma etching, polishing, or chemical treatment. At this stage, we can also add a mechanical support layer (e.g.,

106 on **Fig. 1a**) to the membrane to improve its mechanical stability. A support layer with pore size significantly larger than the matrix pore size can be made using polymer phase inversion (polysulfone, polyaramides, polyvinylidene fluoride (PVDF), pyrrolidone (PVP), polyvinylidene fluoride, 5 polyether sulfone etc.) and/or by melting or gluing a pre-fabricated mesh (ex: non-woven polyester, stainless steel mesh).

After attaching the support membrane, the resulting 10 structure can be released from the wafer/substrate by using a mild acid etch (HF, HCl), or by mechanical removal of the wafer.

The resulting CNT membranes can be coated with a thin interfacially-polymerized polyamide layer to alter their 15 rejection properties (See Example 3 for a sample protocol of this procedure).

Fig. 5a shows aligned 1-D nanoparticles 108 on a substrate 402. Methods for growing aligned 1-D nanoparticles on a substrate are known in the art, and any 20 such method can be employed here.

Fig. 5b shows the result of depositing a conformal polymer layer 502 on the 1-D nanoparticles, such that the 1-D nanoparticles are coated by the conformal layer. Conformal layer 502 may or may not also be deposited on 25 substrate 402. Suitable materials for conformal layer 502 include, but are not limited to: polydopamine, polyethyleneimine, polyacrylic acid, poly(methyl methacrylate) or surfactants (e.g. sodium dodecyl sulfate or Triton X® (Dow)).

30 **Fig. 5c** shows the result of infiltrating a matrix polymer precursor 504 between the 1-D nanoparticles, and also above the 1-D nanoparticles.

Fig. 5d shows the result of simultaneously forming matrix layer 104 and porous support layer 106 from matrix precursor 504. The polymerization is performed such that pores form in layers 104 and 106. One of the pores in matrix layer 104 is referenced as 110. A phase inversion process is a preferred approach for simultaneously forming matrix layer 104 and porous support layer 106, but any approach for forming porous layer 104 and 106 from precursor 504 can be employed.

Fig. 5e shows the result of removing substrate 402 from the structure.

Fig. 5f shows the result of depositing active layer 102 on the exposed surface of matrix layer 104. Interfacial polymerization is a preferred approach for forming active layer 102, but any approach for depositing an active layer 102 on matrix layer 104 can be employed.

The approach of **Figs. 5a-f** can significantly expand the range of polymer that can be used in matrix layer 104, because it effectively removes the strict 1-D nanoparticle compatibility requirements for the matrix polymer 105. Specifically, in connection with carbon nanotubes, the matrix polymer is no longer required to wet the carbon nanotube surface or to prevent the aligned nanotube array from collapsing under the excessive surface tension forces during infiltration. This approach opens up a way to create membranes having aligned 1-D nanoparticles with various different matrix polymers. Example 1 gives a sample protocol for membrane fabrication using m-polyaramid fill.

In some cases, it is preferred for infiltrating the matrix precursor to result in the formation of an excess layer on top of the 1-D nanoparticles (e.g., as on

Fig. 5c). This excess layer can be removed partially or completely (i.e., be reduced to a predetermined thickness) prior to forming the porous support layer. Having an excess amount of material present at the infiltration stage facilitates complete infiltration of the 1-D nanoparticles.

The following description provides several illustrative examples of the above-described principles, where the 1-D nanoparticles are carbon nanotubes (CNTs).

Example 1: Fabrication of reinforced membrane using phase inversion.

Membranes in this example include an aligned carbon nanotube array partially or fully infiltrated with a polymer to form a composite layer (104 on **Fig. 1a**) that is supported by a porous polymer layer (106 on **Fig. 1a**), that may or may not include a mesh (woven or non-woven) (306 on **Figs. 3c-d**). The membrane is fabricated by infiltrating the nanotube array with a polymer solution, and then using a phase inversion method to form the porous support (106 on **Fig. 1a**) attached to the matrix layer (104 on **Fig. 1a**) that contains the aligned nanotube array.

Carbon nanotubes were grown using 0.5 nm of Fe and 0.1 nm of Mo as a catalyst deposited over 30 nm of alumina on standard 4" silicon wafer. The catalyst was deposited in e-beam evaporator using very slow, 0.01-0.02 nm/s deposition rates. CNTs were synthesized at 695-720 °C catalyst annealing temperature, 90 mbar synthesis pressure, acetylene concentration 25 sccm, growth temperature 670-720 °C. As-grown nanotubes were approximately 10-15 microns tall.

A 1-4 mg/mL dopamine hydrochloride (Aldrich) was dissolved in 10-50 mM Trizma-HCL buffer (Aldrich) solution

of 8-10 pH range. A desired amount of the dopamine solution was then poured into a container with aligned CNT wafer. The solution was constantly and gently agitated for 10-40 minutes to polymerize dopamine to polydopamine. This procedure leaves an ultrathin polydopamine coating layer (502 on **Fig. 5b**) of about 5-50 nm thick around the CNTs. Then the CNT wafer was washed thoroughly with water for 30 minutes to remove excess polymer solution. The wafers were left in DI water until they were used for polymer infiltration. An optional procedure of soaking the polydopamine-CNT wafer in isopropanol for 1-4 hrs leads to thinner and more uniform polydopamine coatings on CNTs and the substrate. The isopropanol treatment also minimizes flux losses due to polydopamine coating.

A polymer solution of m-polyaramid was prepared by dissolving 5-18 wt% m-polyaramid in n-methyl pyrrolidinone solvent with 1-10 wt% lithium chloride between 70-90 deg C under constant agitation for 1-4 hours. (Other hydrophilic or hydrophobic polymers could also be used (polysulfone, poly(vinylidene fluoride), cellulose acetate).

To prepare the membrane, excess water was squeezed off the polydopamine-CNTs wafer (after taking it out from DI water bath) either with filter paper or with a rubber roller. Then the wafer was soaked in a n-methyl pyrrolidinone bath for 1-5 minutes. Then an excess amount of the m-polyaramid polymer solution was poured onto the wafer and allowed to infiltrate for 0.5-8 hrs (thus the m-polyaramid polymer solution here is an example of 504 on **Fig. 5c**). The excess polymer solution was removed with an applicator/casting knife. The membranes then were transferred to a water bath to initiate phase separation process. Before phase separation the polymer-CNTs membrane can either be attached to woven/nonwoven polymer backing or

used as it is, depending on the desired application. The resulting membrane was released by soaking overnight in 10% HF and rinsed in DI water.

5 **Example 2:** Fabrication of reinforced aligned carbon nanotubes using a parylene porous roof.

Another approach is thin film composite membranes where the top layer of the membrane is a barrier layer supported by a thin composite layer of substantially
10 aligned carbon nanotubes bound in a permeable polymer matrix that is fabricated with the use of a porous roof. Without losing any generality, an example of this layer is a vertically-aligned carbon nanotube layer with diameters ranging from 0.5 nm to 5 nm. The nanotubes in this example
15 are bound by a vapor-deposited poly-xylene (parylene) polymer. The poly-xylene layer can fill the majority of the interstitial space of the CNT array or that interstitial space could be filled by the composite of poly-xylene and another polymer, such as PDMS, epoxy, m-
20 polyaramide, polysulfone, polyethersulfone, poly(vinylidene fluoride), or cellulose acetate. The thin nanotube polymer layer (e.g., 104 on **Fig. 1a**) is attached to a more porous support layer (e.g., 106 on **Fig. 1a**) that is composed either of a polymer or of a polymer reinforced with mesh
25 backing (woven or non-woven). Carbon nanotubes provide enhanced permeability to the top layer of the membrane, define pore opening size distribution, provide mechanical reinforcement, and determine the rejection properties of the membrane. This reinforced membrane can be also
30 modified with additional chemical processes, or with an additional top layer (e.g., 102 on **Fig. 1a**) that would provide additional or modified rejection properties to the membrane as detailed in Examples 3 and 4.

Carbon nanotubes were grown as described in Example 1. The resulting array of vertically aligned CNTs was covered with 30 nm of parylene (type C) to form a roof layer (e.g., 406 on **Fig. 4b**). A top view image at this stage of the process is given in **Fig. 6a**. However, as much as 1000 nm of parylene may be deposited. Pores in the parylene layer can be created if necessary using O₂ or CF₄/O₂ plasma etch (50-100 W for 5-10 minutes). **Fig. 6b** shows an image of the parylene roof layer after this plasma etching.

The CNT array covered by parylene roof layer was infiltrated with a PDMS solution (e.g., 408 on **Fig. 4c**) for 6-12 hours. Hexane, in ratio 2:1 to 5:1 was added to reduce PDMS solution viscosity and improve infiltration. Infiltration was enhanced by treating the sample in an ultrasound bath for 1-2 hours.

Any excess of PDMS on the top of the parylene roof layer was gently removed by wiping with soft paper. One of the functions of the parylene roof layer is holding the carbon nanotube array and preventing its destruction during this wiping procedure. Infiltrated polymer was cured at 70-130 °C for 1-12 hours to form matrix layer 104. An SEM image of the PDMS infiltration is shown on **Fig. 7a**. Here 702 is the substrate and 704 is matrix layer 104. A black line is added to **Fig. 7a** to show the interface between these two regions. **Fig. 7b** shows an image of a similar structure where Pelco Eponate® 12 is used for infiltration instead of PDMS. Here 706 is a Nomex® porous support layer 106 and 708 is matrix layer 104. This membrane had an added Nomex® porous support layer 106 that was described in Example 1. A white line is added to **Fig. 7b** to show the interface between these two regions.

A reinforcing polymer mesh (e.g., 106 on **Fig. 1a**) was gently melted on the top of CNT forest/polymer mixture and

the resulting membrane was released in 10% HF (typically within 20-60 min of placing the sample in HF solution).

After releasing, the membrane was washed in water (5-10 min), dried in vacuum (10-100 mbar) and the catalyst residue from wafer side was etched for 1-5 min by O₂ plasma using 50-100 W power.

The resulting membranes have high gas permeability and Knudsen gas selectivity, which indicates the absence of large size pores.

10

Example 3: Fabrication of IP coating on top on the reinforced CNT membrane

A thin polyamide rejection layer (e.g., 102 on **Fig. 1a**) on polymer nanotube matrix membrane (e.g., 104 on **Fig. 1a**) can be formed by performing the interfacial polymerization (IP) procedure using the following recipe.

Aqueous Phase: 1-3 wt% 1,3 phenylenediamine (MPDA), 0-3 wt% of 3,5 diaminobenzoic acid (DABA), 0.5-2 wt% triethylamine (TEA), 0.5-3 wt% sodium dodecylbenzenesulfonate (SDBS), and 5-8 wt% camphor-10-sulfonic acid (CSA) and 0.5-4 wt% sodium hydroxide in water stirred for 1 hr before use.

Organic Phase : 0.05-0.2 wt/vol benzenetricarbonyl trichloride (TMC) in 0-100 vol% hexanes and 0-20 vol% of chloroform in 0-100 vol% Isopar G solution stirred for 1 hr before use.

Interfacial polymerization (IP) Procedure: Aligned CNTs membrane (e.g., 104 on **Fig. 1a**) with porous polymer membrane support (e.g., 106 on **Fig. 1a**) was partially dried for about 1-5 minutes. The partially-dried CNT-membrane was fixed to a frame and a small amount of aqueous phase

solution was spread on its surface and agitated for 1-5 minutes, after which the solution was drained and squeezed off. Next, the saturated CNT-polymer support membrane was covered with excess organic solution for 1-3 minutes. The
5 excess organic solution was drained off and the membrane was cured in an oven between 60-150 °C for 1-10 minutes to form an ultrathin polyamide film (e.g., 102 on **Fig. 1a**) on the membrane surface.

All the thin film membranes were washed with water to
10 remove unreacted chemicals prior to storage and/or use.

Example 4: Fabrication of CO₂ selective coating on top of the reinforced CNT membrane.

After the membrane including aligned CNT layer 104 and
15 porous support layer 106 was prepared as described in the previous examples, the top surface was coated with poly(trimethylsilyl)pentyne (PTMSP). The thin polymer layer was deposited by spin coating the PTMSP dissolved in cyclohexane (0.5 - 20 mg/mL) at 1000 rpm. The composite
20 membrane was treated with oxygen plasma (5 seconds @20 mW) and then coated with Pebax® 1657 (0.05 - 1 wt% in 70:30 EtOH:H₂O) using the same spin coating method. The resulting structure is as shown on **Fig. 1a**, with active layer 102 being the PTMSP and Pebax® 1657 layer.

25 The membrane prepared with this recipe showed high selectivity to CO₂ over N₂ and high flux.

Table 2. Gas permeability and selectivity of modified aligned CNT membranes.

	CO ₂ Flux (GPU)	N ₂ Flux (GPU)	CO ₂ /N ₂ selectivity
Membrane1	1090	77	14
Membrane2	931	24	39

Here Membrane1 and Membrane2 are two samples having the above-described structure.

5 The preceding description has been by way of example as opposed to limitation, so many variations and elaborations of the above-described principle also constitute practice of the invention. For example, ultrasonic welding or thermal welding or gluing can be used
10 to seal the membrane within a plastic carrier using a polymeric washer layer. The function of the "washer" layer is to prevent the membrane from cracking during handling from contact with a sharp edge of the main plastic carrier.

CLAIMS

1. A selectively permeable membrane comprising:

a porous support layer;

5 a matrix layer disposed on the porous support layer and comprising a porous matrix polymer and a plurality of 1-D nanoparticles disposed within the porous matrix polymer, wherein the 1-D nanoparticles are substantially vertically aligned, and wherein the 1-D nanoparticles
10 substantially extend through the matrix layer; and

an active layer disposed on the matrix layer, wherein the active layer and the porous matrix polymer have different compositions;

wherein the active layer provides species-specific
15 fluid transport.

2. The membrane of claim 1, wherein the 1-D nanoparticles are selected from the group consisting of: open-ended carbon nanotubes, close-ended carbon nanotubes, carbon
20 fibers, nanowires, nanorods, and nanotubes.

3. The membrane of claim 1, wherein a thickness of the matrix layer is from about 100 nm to about 100 μm .

25 4. The membrane of claim 1, wherein a thickness of the active layer is from about 0.3 nm to about 500 nm.

5. The membrane of claim 1, wherein the active layer is a gas-selective layer.

6. The membrane of claim 1, wherein the active layer is a liquid separation layer for solvent-solute separation.

5 7. The membrane of claim 1, further comprising a woven or non-woven fabric or mesh disposed in the porous support layer.

8. The membrane of claim 1, further comprising one or more
10 anti-fouling layers disposed on the active layer and/or on the porous support layer.

9. A method of making a selectively permeable membrane, the method comprising:

15 i) forming vertically aligned 1-D nanoparticles on a substrate;

ii) infiltrating a matrix precursor between the 1-D nanoparticles;

20 iii) forming a porous polymer matrix from the matrix precursor to provide a matrix layer comprising the porous polymer matrix and the vertically aligned 1-D nanoparticles, wherein the 1-D nanoparticles substantially extend through the matrix layer;

25 iv) forming a porous support layer on top of the matrix layer;

v) separating the matrix layer from the substrate; and

vi) forming an active layer on an exposed surface of the matrix layer, wherein the active layer provides species-specific fluid transport.

10. The method of claim 9, wherein the 1-D nanoparticles
are selected from the group consisting of: open-ended
carbon nanotubes, close-ended carbon nanotubes, carbon
5 fibers, nanowires, nanorods, and nanotubes.

11. The method of claim 9, further comprising:
depositing a porous roof layer on the 1-D
nanoparticles after said forming vertically aligned 1-D
10 nanoparticles and prior to said infiltrating a matrix
precursor, wherein the substrate and roof layer are
vertically separated.

12. The method of claim 9, further comprising:
15 depositing a conformal polymer layer on the 1-D
nanoparticles after said forming vertically aligned 1-D
nanoparticles and prior to said infiltrating a matrix
precursor.

20 13. The method of claim 9, wherein the active layer is
formed by interfacial polymerization.

14. The method of claim 9, wherein the infiltrating a
matrix precursor results in formation of an excess layer on
25 top of the 1-D nanoparticles, and wherein the excess layer
is reduced to a predetermined thickness prior to said
forming a porous support layer.

15. The method of claim 9, wherein the porous polymer matrix and the porous support layer are formed by a single phase inversion process step.

- 5 16. The method of claim 9, wherein the porous polymer matrix and the porous support layer are formed by distinct phase inversion process steps.

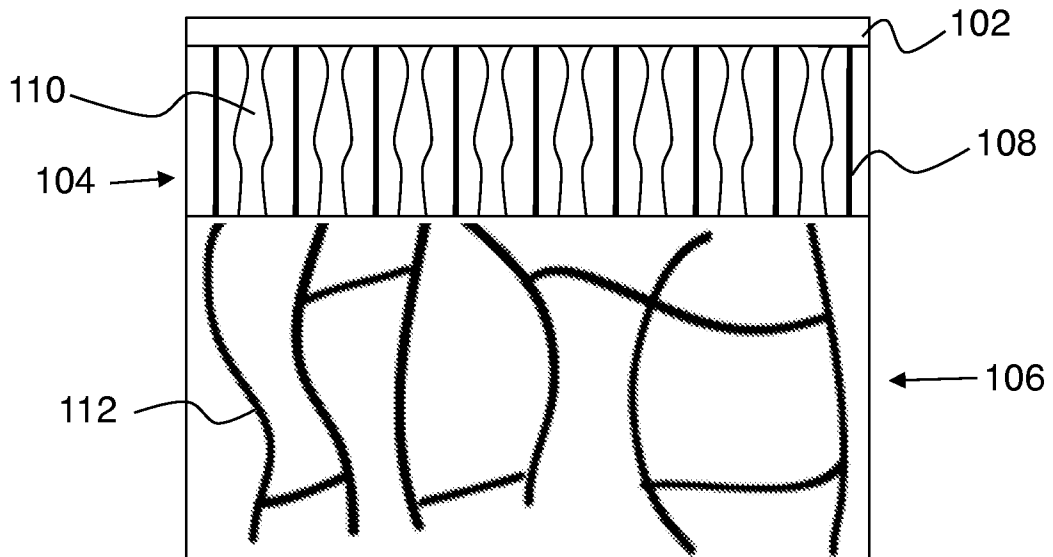


Fig. 1a

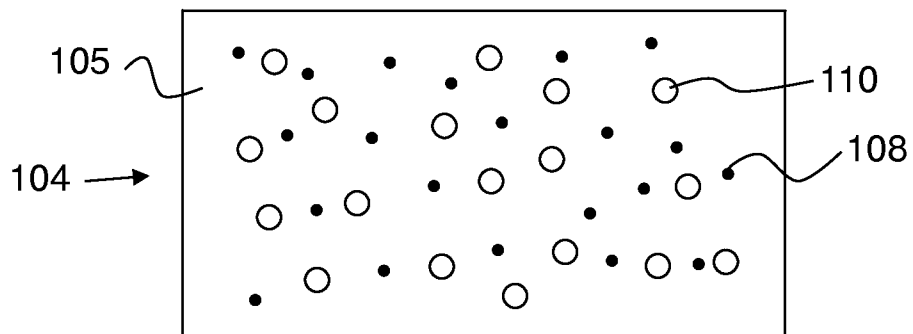


Fig. 1b

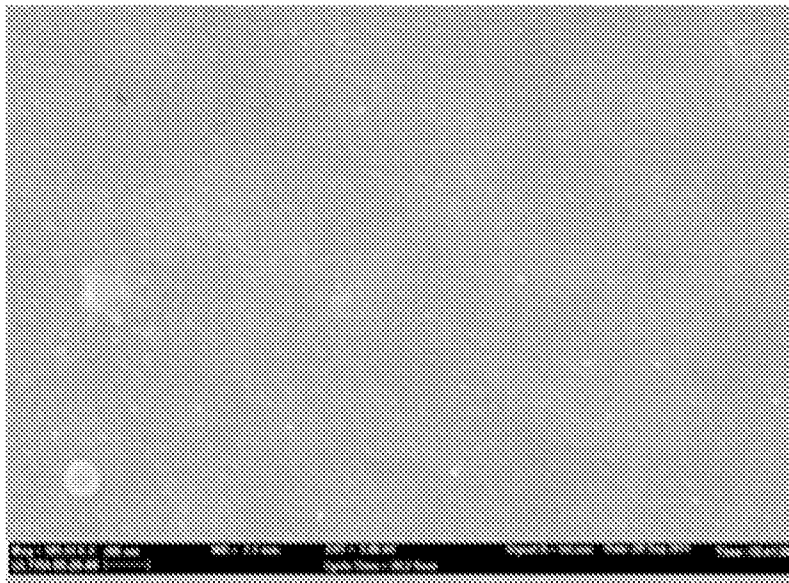


Fig. 2a

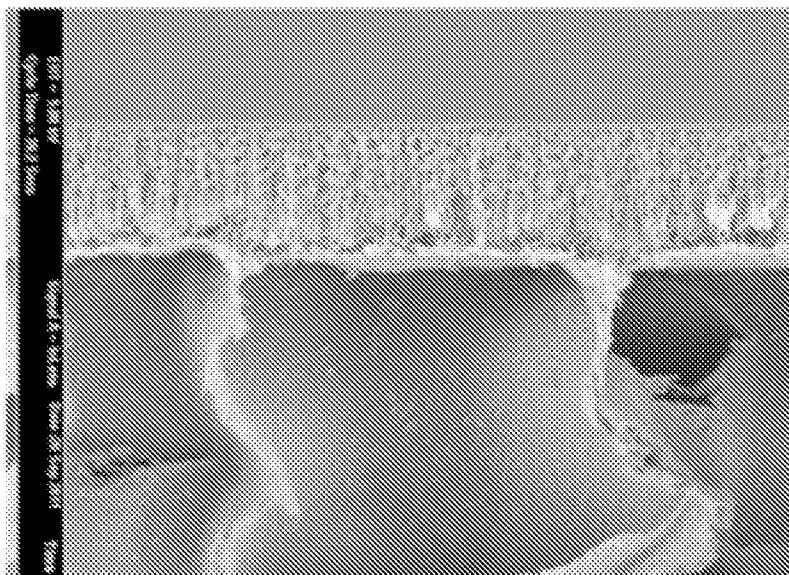


Fig. 2b

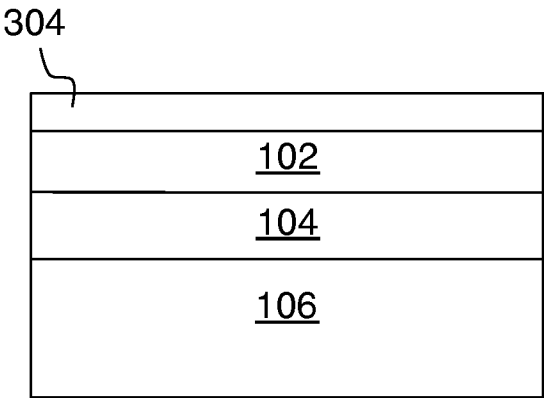


Fig. 3a

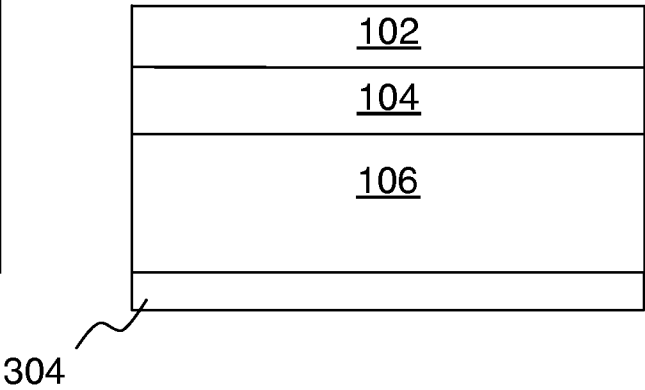


Fig. 3b

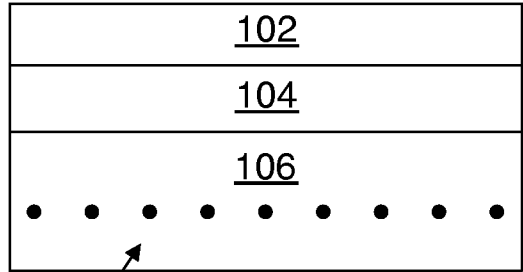


Fig. 3c

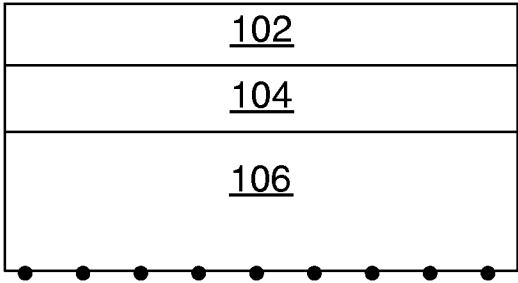


Fig. 3d

4/8

Fig. 4a

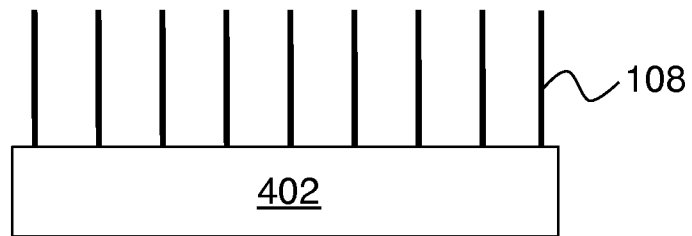


Fig. 4b

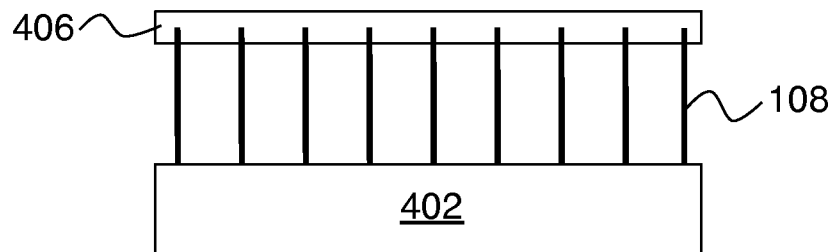


Fig. 4c

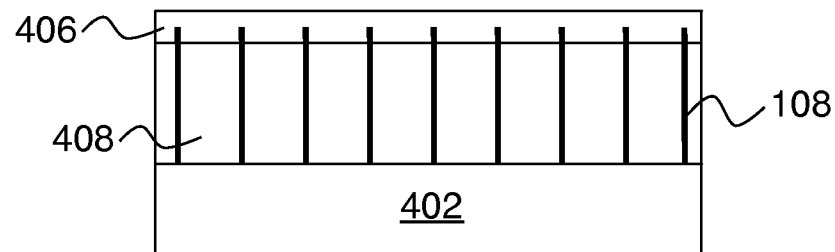


Fig. 4d

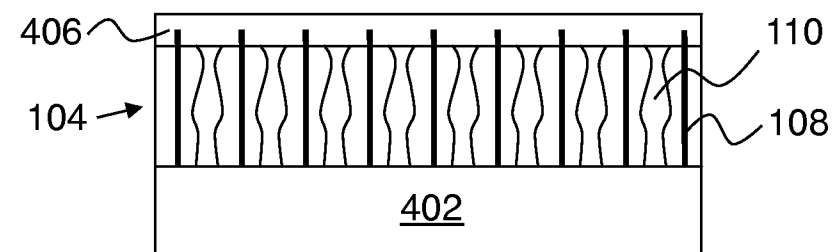


Fig. 4e

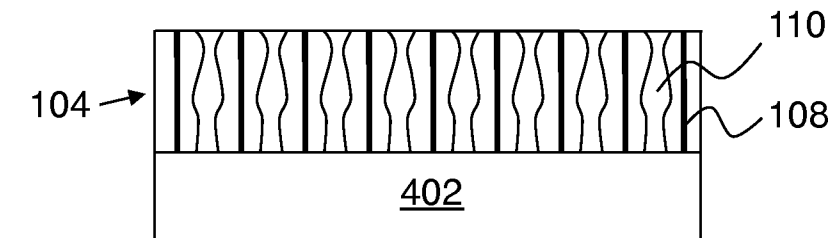


Fig. 4f

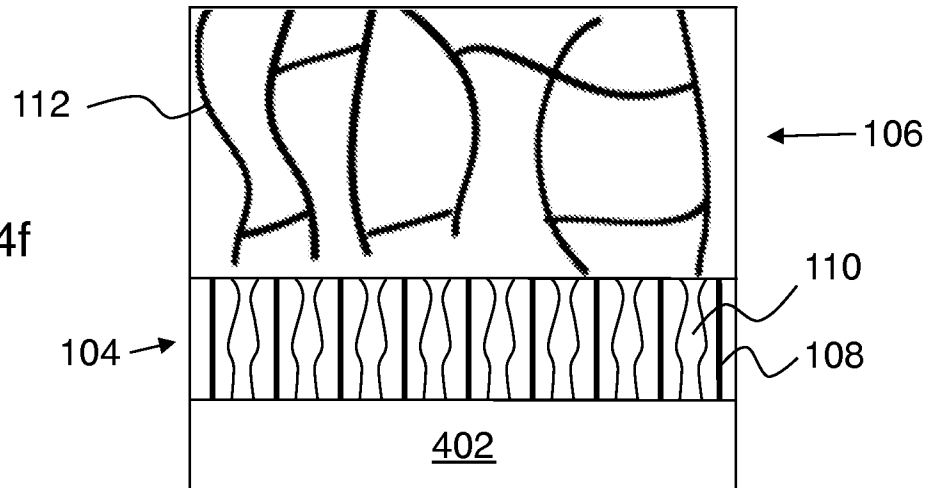


Fig. 4g

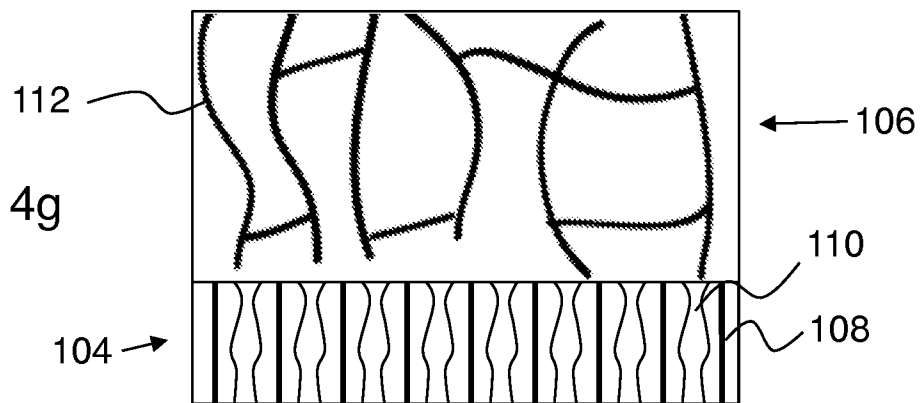


Fig. 4h

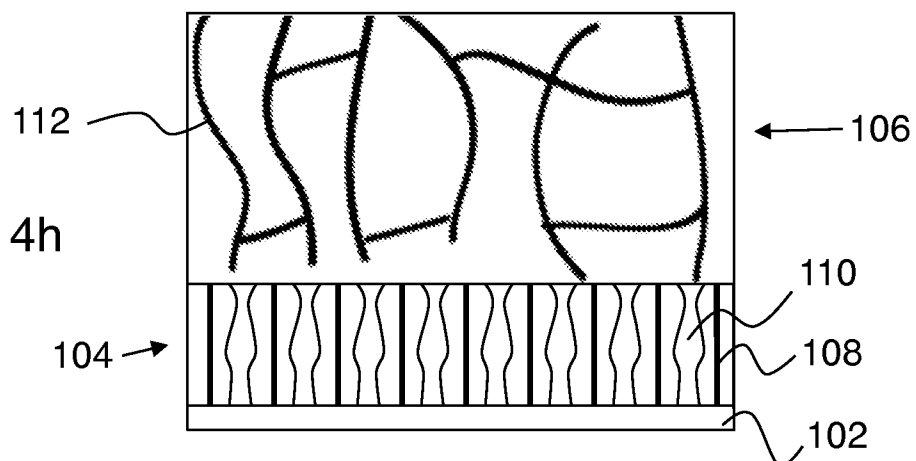


Fig. 5a

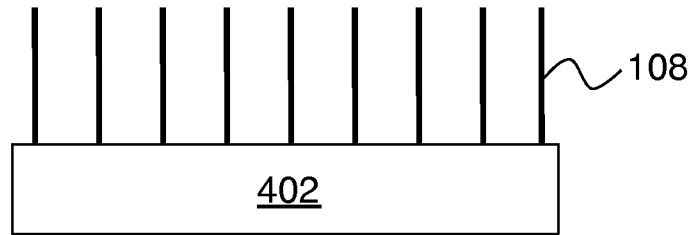


Fig. 5b

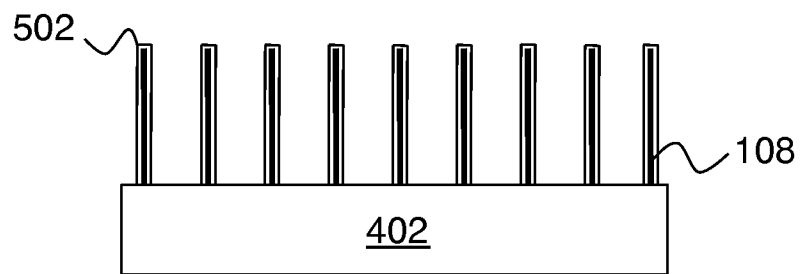


Fig. 5c

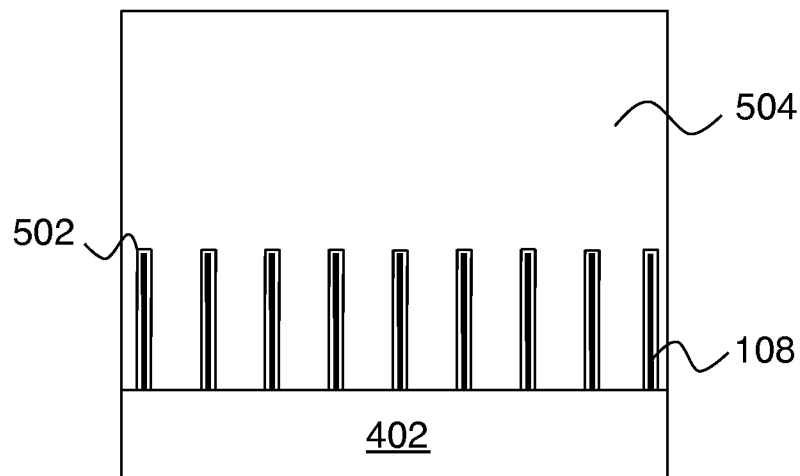


Fig. 5d

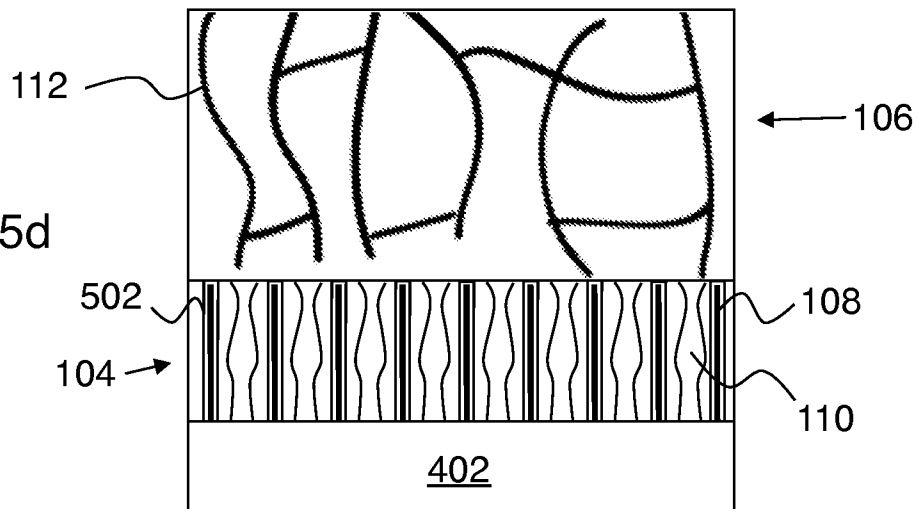


Fig. 5e

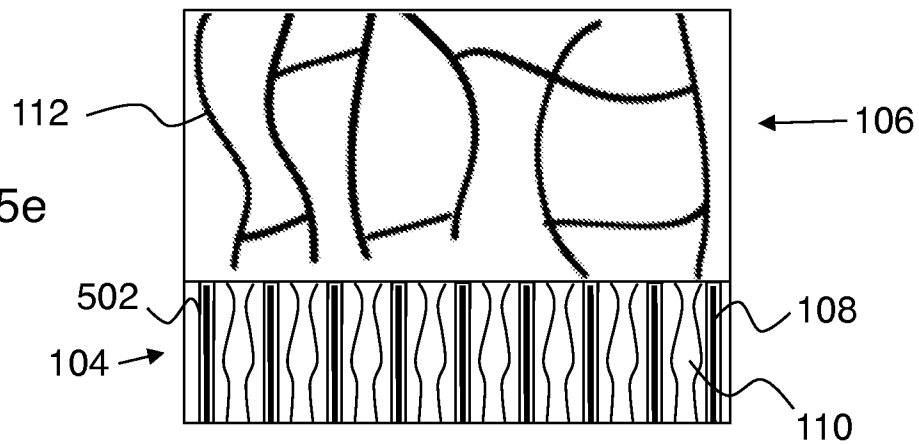
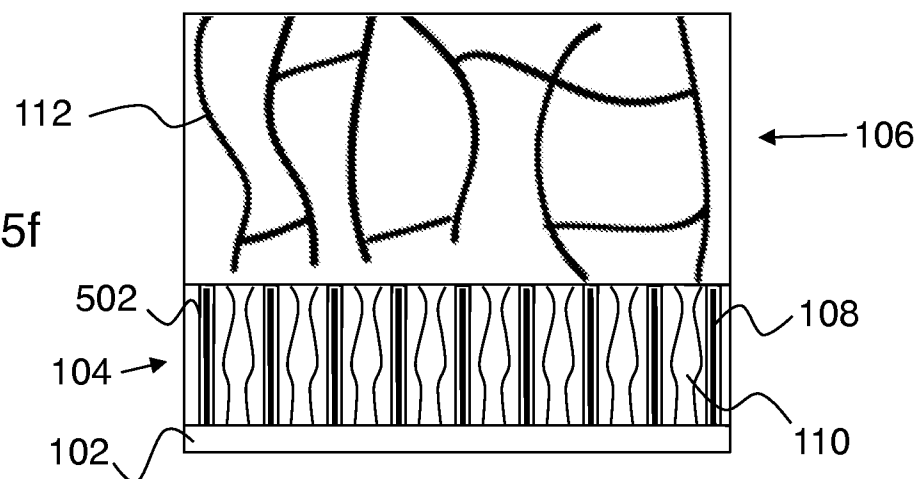


Fig. 5f



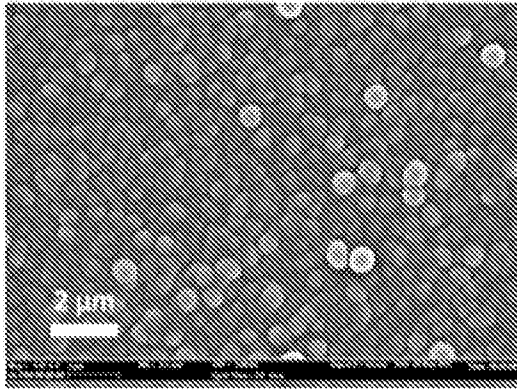


Fig. 6a

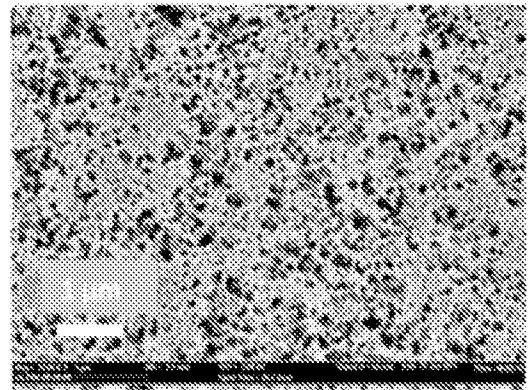


Fig. 6b

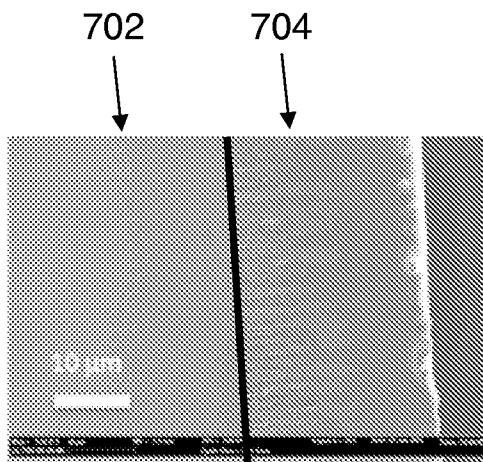


Fig. 7a

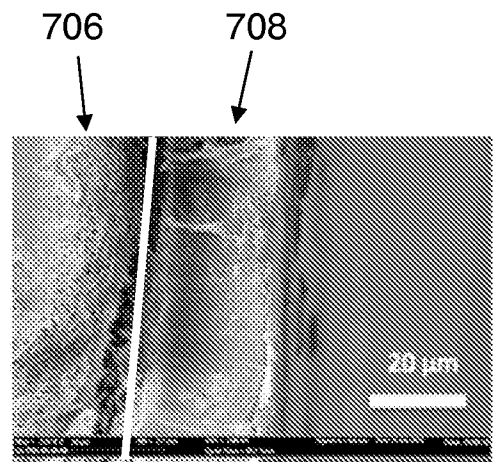


Fig. 7b