

TITLE OF INVENTION

LIGAND BOUND MBP MEMBRANES, USES AND METHOD OF MANUFACTURING **FIELD OF THE INVENTION**

[0001] The invention relates to ligand-bound, multi-block polymer (“MBP”) isoporous materials, their preparation and uses in analytical, detection and separation protocols for the laboratory, scale-up or commercial environment, such as, but not limited to separation techniques necessary for protein purification and production processes, and in-particular, as replacements for column-based affinity separation, as well as sensors for monitoring and detecting analytes of interest.

BACKGROUND OF THE INVENTION

[0002] Protein purification is a critical and challenging aspect in the biomolecule separations market, from R&D to large-scale manufacturing. It is widely acknowledged that a key bottleneck for the entire protein purification process involves the numerous separation protocols. One aspect of current protein purification involves affinity separations that use porous membranes, or supported porous materials with interconnected pores of more than one size regime. Often, the porous membranes useful for affinity separations are formed by linking reactive groups (carboxylic acid groups are disclosed among others) to biological active agents, e.g., Protein A amongst others. The membrane is made of polymeric material. Reactive groups can be directly part of the polymer or formed via precursors which form the reactive group by subsequent treatment.

[0003] The membranes are also formed by attaching (directly or via a linking moiety) an affinity ligand to a reactive bifunctional monomer and polymerizing the affinity ligand / monomer material alone or in the presence of additional monomers and a “porogen,” such as an alcohol. To protect the affinity ligand during the polymerization, it can be protected by a cleavable moiety which, after polymerization, is removed by treatment e.g. with acid.

[0004] Affinity separations can include membranes that have a poly (aryl ether ketone), and a “porogen,” e.g., a polyimide, that have been casted and then pores are formed in the casting by selectively removing the polyimide by chemical reaction. The resulting porous membrane is then

functionalized by reacting the ketone groups in the membrane with an amine bearing an additional attachment group which can be used in further attachment of various species such as proteins.

[0005] Porous membranes for affinity separations have also been made from copolymers (including copolymers containing (in general) styrene derivatives and alkyl acrylate derivatives) and attached via an amide linkage to “affinity ligand” materials including proteins. The copolymers are not block copolymers that self-assemble, or functionalized by/with hydroxyl or amino groups by reaction with various “activators,” which are then further reacted with affinity ligands (protein A is disclosed).

[0006] Other affinity membranes are formed by casting a solution block copolymer (PEO/PPO polyether) and a polysulfone in an organic solvent, followed by a water quenching step. The resulting polymeric membrane has hydroxyl groups on the surface which are then further derivatized to covalent bound biological materials to the membrane. The copolymer is then derivatized prior to casting and the hydroxyl groups freed after membrane formation.

[0007] Membranes from microphase separation structures are prepared from self-assembled block polymer derived from styrenes and an alkyl acrylate with a “polar group. Copolymer membranes containing a carboxyl group-bearing monomer unit where one or more of sugars, lipids, proteins, peptides and composites thereof are also known.

[0008] Interest in membrane chromatography has gradually increased over the past decade, but widespread commercial adoption of membrane chromatography as a replacement for column chromatography has been hindered by limitations in both the variety of available materials platforms and a lack of significant technical advances in membrane structure and performance. In particular, commercially available membrane chromatography materials have been built on conventional membrane structures, which suffer from broad pore size distributions. This pore size variation causes uneven flow patterns across the membrane, broadening breakthrough curves and diminishing media capacity. In current practice, breakthrough curves are sharpened by stacking layers of membrane together so the average permeability along streamlines is rendered more uniform. Chromatography devices in which a stack of membrane layers replaces the more typical column of packed beads have been proposed (See for example WO2000050888A1) but the depth of

the column is severely limited by the pressure required to drive flow through a stack of membranes with submicron pores.

[0009] However, despite major progress in understanding protein expression, structure, and function, the purification of proteins from complex mixtures remains a significant challenge for protein developers at all process scales and it requires an array of separation techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] **Figure 1** is an illustration depicting general hierarchical porosity of a MBP material. Multiple length scales of porosity are depicted.

[0011] **Figure 2** is an illustration depicting affinity ligands on the surface of a porous block copolymer film.

[0012] **Figure 3** is an illustration depicting membrane surface modification with Protein A ligand with EDC

DETAILED DESCRIPTION OF THE INVENTION

[0013] Block copolymer, terpolymer, tetrapolymer, collectively multi-block polymer (MBP) materials/structures are disclosed with at least a portion of the material/structure formed through self-assembly such that the material or structure is hierarchically porous (has pores of multiple length scales). The self-assembled polymer materials contain at least one of macro, meso or micro pores, at least some of which are isoporous. Micropores are defined as having a diameter of 0.1 to 1 nm. Mesopores are defined as having a diameter of 1 nm to 200 nm. Macropores are defined as having a diameter of 200 nm to 1000 μm .

[0014] In one embodiment the self-assembled polymer materials contain mesopores or micropores that have a narrow pore size distribution, and the MBP material or structure is modified partly or completely with an affinity ligand (or linker which is used to attach an affinity ligand).

The polymer materials are formed into films, supported or unsupported, pleated or non-pleated, three-dimensional pleated configurations that are planar, circumferential or spiral in shape, as liners or inserts for various vessels, tubes, or cuvettes. The material can be formed into various shapes, e.g. beads, spheres, or multidimensional solid media.

[0015] In some embodiments, the MBPs comprise mesopores. In an embodiment, the mesopores are in the range of about 1 nm to about 200 nm. In an embodiment the mesopores are in the range of about 3 nm to about 200 nm. In an embodiment the mesopores are in the range of about 5 nm to about 200 nm. In an embodiment the mesopores are in the range of about 5 nm to about 100 nm. In an embodiment, the mesopores are in the range of about 5 nm to about 50 nm. In some embodiments, the MBPs comprise micropores. In an embodiment, the micropores are in the range of about 0.1 nm to about 1 nm.

[0016] In some embodiments, the MBPs comprise macropores. In an embodiment, the macropores are in the range of about 200 nm to about 1000 μm . In an embodiment, the macropores are in the range of about 200 nm to about 100 μm . In an embodiment, the macropores are in the range of 200 nm to about 10 μm . In an embodiment, the macropores are in the range of 1 μm to about 10 μm . In an embodiment, the macropores are in the range of about 500 nm to about 10 μm .

[0017] The MBPs structure/material of the present invention provide a solution to difficulties with existing column affinity chromatography by using the high-capacity MBP membrane structure/films that are modified to partly or completely function as membrane adsorbers with the same or better separation qualities in a fraction of the processing time relative to existing column affinity chromatography media. Current downstream purification processes utilize multiple steps and is performed batch-wise. The first step in the purification line is a column-based affinity separation, which is widely acknowledged as a key bottleneck for the entire process. The affinity column represents nearly 25% of the total process time, leaving downstream equipment idle and resulting in low manufacturing efficiencies. This step also represents the largest labor expenditure in the entire purification line. Furthermore, the high volume of consumables required for column chromatography contributes considerably to the high costs of protein development and manufacturing. The existing bottleneck caused by existing column affinity chromatography is

alleviated through dramatic decrease in processing time with corresponding reductions in manufacturing costs, and at the same time increasing production efficiencies when the MBPs structure/material membrane/film adsorbers of the present invention are used.

[0018] In addition to debottlenecking existing purification processes, the present invention provides process improvements by making possible highly uniform flow through a single layer of membrane. In configurations where isoporous meso or micro pores form a continuous layer on the downstream surface of the membrane, these pores provide a uniform flow resistance much greater than that provided by the larger heterogeneous pores, although smaller than the resistance to flow that occurs in a packed column of similar pore size. When the membrane is packaged as a filtration device utilizing a small number of membrane layers (preferably no more than three, more preferably one) the resistance of the isoporous layer causes the flow velocity to be uniform everywhere, thus efficiently utilizing all of the binding sites. Further, in such a device, which, for example, can be a cartridge containing a pleated pack, a crossflow cassette or module containing flow channels bounded by flat sheets of membrane, or a spiral wound cartridge such as is common in the water filtration industry, particulate or large molecule filtration can be combined in one step with chromatographic separation, thus reducing the total number of unit operations required.

[0019] The multi-block polymers of the present invention rely on self-assembly techniques to form the membrane films, such as those disclosed in U.S. Patent Publication a No. 9,527,041, or the hybrid material of International Publication No. WO2015048244, each of which incorporated by reference in its entirety.

[0020] Or, as described in Hierarchically Porous Materials from Block Copolymers, Dorin et al., the entirety of which are incorporated by reference. The membrane films are modified to include bound ligands, and provide high selectivity contemporaneously with high through-put. The process provides the films with a hierarchically porous structure having very high surface areas and combines macroporous continuous domains with mesoporous wall structures in a single, scalable material. The macroporous structural features provide for convective solution flow, offering rapid processing, while the mesoporous walls create high surface areas, offering the unique potential for high density affinity functionalizations. The addition of high-capacity potential through mesoporous

matrix structures makes them suitable for industrial application in the biomolecule separations market.

[0021] The combination of uniform mesoporosity and macroporosity in the multi-block polymers of the present invention provide membrane of high flux and high surface area. The macroporous regions allow high flux while the uniform mesopores provide high surface areas and uniform flow distribution. The affinity ligand on the membrane surface provides a platform for affinity-based interactions of species/analytes of interest with the membrane.

[0022] The MBP material of the present invention, whether in film or three-dimensional configuration, are formed from one of purely organic templates, hybrid materials, combinations thereof, alone, or combined with surface located or embedded nanoparticles, and optionally functionalized.

[0023] The present invention utilizes the self-assembly technique for preparing the multi-block polymers of the present invention with at least one block containing functional groups to form hierarchically porous membranes with very high surface areas. At least one block in the MBP of the membrane is modified with covalent or noncovalent links with an affinity ligand. Such structures do not require a substrate for formation and combine macroporous continuous domains with mesoporous wall structures in a single, scalable structure. The macroporous structural features provide for improved convective solution flow, offering rapid processing, while the mesoporous walls create high surface areas, offering the potential for high density surface functionalizations. The addition of high-capacity potential through mesoporous matrix structures has highly promising implications for industrial application in the protein separations market compared to known membranes.

[0024] In some applications the isoporous layer occupies the entirety of the downstream surface of the membrane, especially in embodiments where the material is a membrane that is pleated.

[0025] The inventive hierarchically porous multi-block polymer (“MBP”) material/structure is functionalized with an affinity ligand. The MBP contains two or more chemically distinct blocks (A-B), also A-B-C or B-A-C terpolymers, or are higher order multi-block copolymer systems of the

form A-B-C-B, or A-B-C-D, or A-B-C-B-A, or A-B-C-D-E, or other variable arrangements of these higher order systems. The multiblock copolymers can be synthesized by methods known in the art. Some examples of synthetic methods for the multiblock copolymers include: anionic polymerization, cationic polymerization, reversible addition-fragmentation chain-transfer polymerization, atom-transfer radical polymerization, and any combinations of the listed synthetic methods. Each block can, but does not necessarily contain a mixture of chemistries, provided adjacent blocks are sufficiently chemically distinct, thus enabling self-assembly. In an embodiment, at least one block of at least one block copolymer comprising the MBP comprises a hydrophilic or hydrogen-bonding block chemistry. For example, suitable hydrophilic or hydrogen bonding block chemistries include: poly((4-vinyl)pyridine), poly((2-vinyl) pyridine), poly(ethylene oxide), poly(methacrylate), poly(methyl methacrylate), poly(dimethylethyl amino ethyl methacrylate), poly(acrylic acid), poly(dimethyl acrylamide), poly(styrene sulfonate), poly(2-hydroxyethyl methacrylate), poly(acrylamide) and poly(hydroxystyrene)). In some embodiments, at least one block copolymer comprising the MBP further comprises at least one hydrophobic block chemistry. Examples of suitable hydrophobic block chemistries include: poly(styrene), poly(isoprene), poly(butadiene), poly(ethylene), poly(propylene). Examples of suitable block copolymers include for example, poly(isoprene-b-styrene-b-4-vinyl-pyridine), poly(isoprene-b-styrene-b-2-vinyl-pyridine), poly(isoprene-b-styrene-b-ethylene oxide), poly(isoprene-b-styrene-b-methacrylate), poly(isoprene-b-styrene-b-methyl methacrylate), poly(isoprene-b-styrene-b-dimethylethyl amino ethyl methacrylate), poly(isoprene-b-styrene-b-acrylic acid), poly(isoprene-b-styrene-b-dimethylethyl amino ethyl methacrylate), poly(isoprene-b-styrene-b-dimethyl acrylamide), poly(isoprene-b-styrene-b-styrene sulfonate), poly(isoprene-b-styrene-b-2-hydroxyethyl methacrylate), poly(isoprene-b-styrene-b-acrylamide), poly(isoprene-b-styrene-b-hydroxystyrene), poly(styrene-b-4-vinylpyridine), poly(styrene-b-2-vinylpyridine), poly(styrene-b-ethylene oxide), poly(styrene-b-methacrylate), polystyrene-b-methyl methacrylate), poly(styrene-b-dimethylethyl amino ethyl methacrylate), poly(styrene-b-acrylic acid), poly(styrene-b-dimethyl acrylamide), poly(styrene-b-styrene sulfonate), poly(styrene-b-2-hydroxyethyl methacrylate), poly(styrene-b-acrylamide), poly(styrene-b-hydroxystyrene), poly(propylene-b-4-vinylpyridine), poly(styrene-b-2-vinylpyridine-b-isoprene-hydroxystyrene), poly(styrene-b-butadiene-b-dimethyl acrylamide-b-isoprene-styrene-4-vinylpyridine). The above polymers are listed as illustrative examples and other

chemistries, combinations and block numbers and orientations are possible as long as the materials meet the structural characteristics of the invention.

[0026] The blocks are not necessarily separated by a single unit or several units of a differing chemistry which might not be considered a distinct “block.” Blocks can but are not necessarily linked with a gradient of chemistries between blocks (i.e. there is no sharp transition in chemistry at a single unit in the copolymer). Hierarchically porous materials generally have interconnected pores of more than one size regime. The films contain mesopores, as well as macropores. The mesopores exhibit a narrow pore size distribution due to the self-assembly of the block copolymers during material or structure formation, such as a film. The materials have an overall isotropic or asymmetric structure. The membrane surface is partially or completely surface modified with an affinity ligand, shown below.

[0027]

[0028] Affinity ligands are molecules that are capable of binding with very high affinity to either a moiety specific for it or to an antibody raised against it. In protein-ligand binding, the ligand is usually a signal-triggering molecule, binding to a site on a target protein. In DNA-ligand binding, a ligand is usually any small molecule or ion or even a protein that binds to the DNA double helix. The binding occurs by intermolecular forces, such as ionic bonds, hydrogen bonds and van der Waals forces. The docking (association) is usually reversible (dissociation). Incorporation of such ligands into a block copolymer, which is in the form of a hierarchically porous film, allows for the capture and purification of a particular biomolecular moiety by affinity chromatography using the appropriate affinity ligand. In one embodiment, Protein A is an affinity ligand attached to the block copolymer via chemical reaction either directly or through a linking molecule. The resulting films that have covalently bound Protein A can be used to capture or purify human immunoglobulin (IgG). Other embodiments of affinity ligands are Protein G, Protein A/G and Protein L. Still other examples of affinity ligand / target moiety include biotin (ligand)-streptavidin (moiety), digoxigenin (ligand)-anti-DIG-antibody and dinitrophenol (ligand)-anti-DNP-antibody, and nucleic acids. For

covalent attachment of affinity ligands, examples of suitable functional groups on the material surface are: carboxylic acids, hydroxyl groups, amino groups, thiol groups and other groups that contain an ionizable or removable hydrogen. An embodiment of the covalent attachment of an affinity ligand is the attachment of Protein A to a carboxylic surface of a film. This is achieved by first activating the MBP material surface with 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide chloride (EDC). Subsequently the activated material surface is exposed to the affinity ligand (Protein A), forming a covalent attachment of the ligand to the material surface.

[0029] Suitable linking agents include, but are not limited to, an imidoester such as dimethyl suberimide; a N-hydroxysuccinimide-ester such as BS3; carbodiimides such as EDC, SMCC or its water-soluble analog, sulfo-SMCC, DCC or DIC; benzotriazole derivatives such as BOP, HATU, PyBOP and the like; anhydride or mixed anhydride formation via acid halides, acyl azides or sulfonyl halides; or an intermediate nitrophenyl ester. Although carboxylic acids are preferred, other coupling agents may be used when other kinds of functional groups exist on the block copolymer or block copolymer film.

[0030] In another embodiment, the MBP material bears a moiety selected from the group consisting of: a chemically reactive group suitable for reaction with a reactive group of a graftable compound to covalently graft the compound to the material; a pH sensitive group, a group suitable for direct immobilization of an analyte; a dye, fluorophore, chromophore, or quencher; an immobilized protein; and immobilized natural or artificial nucleic acid molecules.

[0031] In another embodiment, the MBP material comprises at least one of the following side chains or groups: hydroxyl, amino, carboxyl, polyethylene glycol, alkyl, maleimide, succinimide, acyl halide, sulfhydryl, or azide.

[0032] In another embodiment at least one functionalized monomer is an amino methacrylate, an amino acrylate, acrylic acid, dimethyl acrylamide, or methacrylic acid.

[0033] In another embodiment, the MBP material surface is modified with affinity ligand by non-covalent attachment, e.g. adsorption or impregnation.

[0034] In another embodiment of the invention the MBP material is the separation media for affinity-based separations, e.g. protein purification, which is used as a bind-and-elute operation where the target species is bound to the affinity ligand to isolate it. Subsequently, the target species can be unbound from the material to recover the target species. In another embodiment of this invention binding a specific impurity is used to remove this impurity from a mixture while the target compound(s) flow through the material.

[0035] Another application of the invention is as part of a sensor, e.g. chemical or biochemical detection and/or quantification. Activation of a particular response on the film, resistance, capacitance, color, upon binding of a target species to the affinity ligand. In this embodiment, the binding of the target species to the affinity ligand invokes a detectable change or response of the material (e.g. change in spectrophotometric profile of membrane), allowing the detection and/or quantification of the target species.

[0036] One or more blocks of the MBP films of the invention are modified with a linker that provides functionality for the subsequent attachment of an affinity ligand; the MBPs of the invention have a three-dimensional block copolymer structure encompassing hierarchical porosity and modified with a linker or affinity ligand, and is not limited to the aspect ratio typical of a “film” or “membrane.” The MBP material may be a monolithic material. The material may be molded or otherwise formed into various three-dimensional shapes. The shapes may contain zones with different porosities or ligands. The modification of the block copolymer with affinity ligand or linker is provided before or after fabrication into a film. The block copolymer modified with linker or affinity ligand relative to the stoichiometry of the block copolymer, by varying the time, temperature, concentration of modifier, etc. The relevant range or degree of modification for most applications is 10-100% of available sites. The MBP films of the invention include more than one affinity ligand or linker, an affinity ligand or linker containing more than one functionality, or affinity ligand or linker in part or completely on more than one polymer block.

[0037] The MBP ligand bearing materials/films of the present invention include conformal coatings of linking material by covalent or non-covalent means, resulting in a physical layer of the

linker or affinity ligand; formation of or immobilization of the material on a support material, to provide mechanical stability.

[0038] The MBP ligand bearing materials/films of the present invention include integration into textiles, or a sensor device.

[0039] The MBP ligand bearing materials/films of the present invention further include micropores in the material/structure, in addition to its mesopore structure, provided by the processing of the MBP to incorporate microporous material into/onto the material/structure (e.g. zeolite, microporous carbon). The micropores are in addition to the mesopores, or replace, in-part or total the micropores provided by the mesopores.

[0040] The MBP films of the invention facilitate control of the geometry and area of material/structure that is modified with affinity ligand or linker. The geometric control is two-dimensional or three-dimensional, or some combination thereof. One embodiment of this geometric control of coating may be patterning, e.g. lithographically. Another embodiment of this geometric control is physically attaching a portion or portions of modified material/structure to unmodified film, or another substrate.

REFERENCE SUBJECT MATTER INCORPORATED IN THEIR ENTIRETY

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Claims

1. A self-assembled polymer material, the material comprising:
 - at least one of macropores, mesopores and micropores, at least some of which are isoporous; and
 - at least one multi-block polymer (MBP) comprising at least two chemically distinct polymer blocks, wherein
 - at least one polymer block of the MBP is a hydrophobic block;
 - at least one polymer block of the MBP is a hydrophilic block; and
 - at least one polymer block of the MBP is functionalized with an affinity ligand, the affinity ligand having an affinity to bind with a target species.
2. The self-assembled polymer material of claim 1, wherein the material is asymmetric or symmetric.
3. The self-assembled polymer material of claim 1, further comprising macroporous domains and mesoporous wall structures in a single structure.
4. The self-assembled polymer material of claim 2, further comprising continuous macroporous domains.
5. The self-assembled polymer material of claim 4, wherein the material is asymmetric and has mesopores and macropores.
6. The self-assembled polymer material of claim 1, wherein
 - a. the affinity ligand is functionalized on the at least one polymer block of the MBP by a covalent bond, or
 - b. the affinity ligand is functionalized on the at least one polymer block of the MBP by a non-covalent bond, or

c. the at least one polymer block of the MBP further comprises a linking molecule, and the affinity ligand is functionalized on the at least one polymer block of the MBP via the linking molecule.

7. A method of preparing the material of claim 1, the method comprising:

- a. modifying a surface of the MBP with an affinity ligand by non-covalent attachment; or
- b. modifying the MBP with a linker that provides functionality for the subsequent attachment of an affinity ligand; or
- c. modifying the blocks of the MBP with an affinity ligand or a linker, to provide the MPB with a three-dimensional block terpolymer structure encompassing a hierarchical porosity with the linker or the affinity ligand, before fabrication into a film; or
- d. varying the amount of MBP modified with a linker or an affinity ligand relative to the stoichiometry of the MBP, comprising varying the time, temperature, and concentration of modifier, to modify 10-100% of available sites; or
- e. conformally coating a linking material by covalent or non-covalent moieties to a surface of the material to provide an integral, but discrete physical layer of a linker or an affinity ligand; or
- f. providing the self-assembled polymer material with micropores by incorporating a microporous material into or onto the material, in addition to the mesopores of the MBP mesopores-macro structure; or
- g. controlling the geometry and area of material that is modified with affinity ligand or linker to arrange
 - i. in two-dimensions, or
 - ii. in three-dimensions, or
 - iii. in a pattern lithographically, or
 - iv. by attaching a portion or portions of modified material to an unmodified film, or another substrate.

8. An article, the article comprising a self-assembled polymer material according to claim 1 immobilized on a support.

9. An article, the article comprising a self-assembled polymer material according to claim 1 integrated with a textile.
10. A sensor comprising the self-assembled polymer material of claim 1.
11. A process separating and/or detecting an analyte of interest, the process comprising contacting a medium containing the analyte of interest with a self-assembled polymer material according to claim 1, and separating the analyte of interest from the medium.
12. The process of claim 11, wherein the analyte of interest is a protein.
13. The process of claim 11, wherein separation involves bind-and-elute operations where the analyte is a target species that binds to an affinity ligand of the self-assembled polymer material.
14. A method of detecting an analyte or species of interest, the method comprising:
 contacting a sensor according to claim 10 with an analyte or species of interest, and
 measuring an optical/electrical change as a result of an interaction between the analyte or species of interest and the affinity ligand.
15. The self-assembled polymer material of claim 3, wherein the macroporous structural features provide improved convective solution flow, rapid processing, and the mesoporous walls create high surface areas, for high density surface functionalization.
16. The process of claim 11 wherein the analyte comprises a nucleic acid.
17. A device comprising a self-assembled polymer material according to claim 1, wherein the self-assembled polymer material is in the form of a pleated pack, as flat sheets in a crossflow cassette or module, or in a spiral wound module.

18. A process utilizing a device according to claim 17 to separate molecules, the process comprising a binding and eluting operation.

19. A process utilizing a device according to claim 18 for the separation of molecules or suspended particles, the process comprising a filtration operation.

20. The self-assembled polymer material of claim 1, wherein the target species is selected from the group consisting of antibodies, proteins, DNA, and nucleic acids.