

## **CHEMICAL PINNING TO DIRECT ADDRESSABLE ARRAY USING SELF-ASSEMBLING MATERIALS**

### **BACKGROUND**

[0001] Structures having components with dimensions on a nanometer scale are being considered for use in the areas of optics, electronics, mechanics, magnetism and so forth. Nanostructures encompass various structures referred to as, for example, nanoparticles, nanotubes or quantum dots, and may potentially be used as building blocks for ordered and complex materials.

[0002] For data storage media, including bit patterned media (BPM) and discrete track media (DTM), the patterning of ultra-high density dot array or line array, with a periodicity as small as 25 nm or less is desirable. However, since optical lithography is limited by the diffraction limit, the resolution of conventional optical lithography is usually limited to about 50 nm half-pitch. Thus conventional optical lithography may not be suitable for fabricating such nanostructures for bit patterned magnetic storage media.

[0003] A high-throughput patterning method is desired for forming nanostructures on a substrate. Self-assembly technology has the potential to provide both ultrahigh-density patterning and high throughput.

### **SUMMARY**

[0004] In one aspect, the invention provides a method including: providing a substrate having a plurality of chemically contrasted alignment features, and depositing a self-assembled material on at least a portion of the substrate, wherein the position and/or orientation of substantially spherical domains of the self-assembled material is directed by the alignment features, to form a nanostructure pattern, and wherein the period of the alignment features is between about 2 times and about 10 times the period of the spherical domains.

[0005] In another aspect, the invention provides an apparatus including a substrate having a plurality of chemically contrasted alignment features, and a self-assembled material on at least a portion of the substrate, wherein the position and/or orientation of substantially spherical domains of the self-assembled material is directed by the alignment features, to form a nanostructure pattern, and wherein the average

spacing of the alignment features is between about 2 times and about 10 times the period of the spherical domains.

[0006] In another aspect, the invention provides a method including: providing a substrate having a plurality of discrete chemically contrasted alignment features, and depositing a self-assembled material on at least a portion of the plurality of chemically contrasted alignment features, wherein the position and/or orientation of substantially cylindrical domains of the self-assembled material is directed by the alignment features, to form a laminar pattern, and wherein the period of the alignment features is between about 2 times and about 10 times the period of the cylindrical domains.

[0007] In another aspect, the invention provides an apparatus including a substrate having a plurality of discrete chemically contrasted alignment features, and a self-assembled material on at least a portion of the plurality of chemically contrasted alignment features, wherein the position and/or orientation of substantially cylindrical domains of the self-assembled material is directed by the alignment features, to form a laminar pattern, and wherein the average spacing of the alignment features is between about 2 times and about 10 times the period of the cylindrical domains.

[0008] In another aspect, the invention provides a method including: forming a first plurality of spaced dots in a servo area of a substrate, using a lithographic process to form a second plurality of spaced dots in a bit area of a substrate, and depositing a self-assembled material on at least a portion of the bit area, wherein the position and/or orientation of domains of the self-assembled material is directed by the second plurality of spaced dots, to form a nanostructure pattern in the bit area.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 is a schematic representation of a fabrication process in accordance with one aspect of the invention.

[0010] FIG. 2 is a schematic representation of a block copolymer.

[0011] FIG. 3 is a cross-sectional view of a substrate.

[0012] FIG. 4 is a cross-sectional view of a substrate.

[0013] FIGs. 5, 6 and 7 are schematic representations of dot patterns.

[0014] FIGs. 8, 9, 10 and 11 are schematic representations of portions of patterned media constructed in accordance with an aspect of the invention.

[0015] FIG. 12 is a photomicrograph of a portion of a patterned media in accordance with an aspect of the invention.

[0016] FIG. 13 is a schematic cross-sectional view of a portion of another patterned media constructed in accordance with an aspect of the invention.

[0017] FIG. 14 is a schematic cross-sectional view of a portion of another patterned media constructed in accordance with an aspect of the invention.

[0018] FIG. 15 is a photomicrograph of a portion of another patterned media in accordance with an aspect of the invention.

[0019] FIG. 16 is a plan view of a patterned surface that can be used in the fabrication of the patterned media of FIG. 15.

[0020] FIGs. 17, 18 and 19 are schematic representations of a cross-section of another patterned media constructed in accordance with an aspect of the invention.

[0021] FIG. 20 is a schematic representation of a data storage disc template in accordance with an aspect of the invention.

[0022] FIG. 21 is a flow diagram that illustrates the method of an aspect of the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

[0023] This invention relates to methods of fabricating nanostructured devices and to devices fabricated using such methods. In one aspect, the invention provides a method for achieving long-range order and precise positional control in naturally self-assembled nanostructures.

[0024] The invention can be used in the fabrication of data storage media. Data storage media generally includes a servo area and a bit area. The servo area includes information that is used to control the position of a recording head and the timing of read and write operations. The bit area is used to store information that is written to and read from the media. In one aspect, the invention allows the integration of self-assembly process into nanoimprint template fabrication of BPM for both a bit area having high-density periodic dot patterns and a servo area having medium-to-high density periodic/non-periodic dot/line patterns.

[0025] In another aspect, the invention uses a substrate structure with a chemical contrast surface pattern that can be used to direct the self-assembly, or self-organization,

of an array of nanostructures. As used in this description, a chemical contrast substrate refers to a substrate having regions or materials that exhibit different chemical preferences, or affinities, for different components of a block copolymer. The regions or materials can have little topographic difference. The regions or materials serve as alignment features that direct the self-assembly of the nanostructures. Self-assembly means the formation of periodic nanostructures of self-assembling materials, such as block copolymers and nanoparticles. The periodic nanostructures can form spontaneously in a relatively large area according to thermodynamic properties.

[0026] A substrate having a chemical contrast can be used to direct the positioning of block copolymer spherical or cylindrical nanodomains with domain periods of 25 nm or less, corresponding to an areal density of  $\geq 1 \text{ Tdot/in}^2$  as desired for the template fabrication of bit patterned media (BPM). Referring to the drawings, FIG. 1 schematically illustrates a fabrication process in accordance with one aspect of the invention.

[0027] In FIG. 1, a disc 10 includes a substrate 12 and has a surface pattern 14 formed on the substrate. The surface pattern includes a chemical contrast surface pattern having a plurality of regions 16 in or on a surface 18. The regions 16 serve as alignment features for subsequently deposited nanostructures. While only a few regions 16 are shown in FIG. 1 for clarity, it will be appreciated that many more regions 16 may be used in a practical device. The regions and surface have different affinities for material that are to be subsequently deposited on the substrate, and serve to direct the position and/or orientation of nanostructures. The regions 16 can be created by conventional lithography, such as e-beam lithography, nanoimprinting, extreme-ultraviolet (EUV) lithography, 193 nm lithography, 248 nm lithography, X-ray lithography, etc.

[0028] The half-pitch of the surface pattern 14 can be, for example, tens to hundreds of nanometers. In this example, the regions 16 have a substantially circular shape in the plane of the surface 18. The regions 16 are also referred to as dots.

[0029] A self-assembled material is used to fabricate a pattern 20, whose long-range order and positional accuracy is directed by surface pattern 14. In one example, the self-assembled pattern is fabricated using block copolymers. The components of the block copolymer will position themselves on the surface of the substrate in a pattern that

is directed by the chemical contrast pattern of the substrate. One domain of the block copolymer can be removed to leave the domains 22 in the pattern 20. In one example, the remaining domains 22 have a substantially spherical shape.

[0030] The period ratio between substrate pattern and block copolymer pattern can vary in a range from 1:1 to 10:1. In addition, the lattice structure in substrate chemical contrast pattern is not necessarily the same as that in the block copolymer pattern. Furthermore, the chemical contrast pattern need not be periodic.

[0031] In one example, the size of the alignment dots 16 is smaller than the size of the block copolymer domain 22 when measured in a lateral direction, and the volume of the alignment dots is much smaller than that of the block copolymer domains.

[0032] FIG. 2 is a schematic representation of a block copolymer 30. The block copolymer includes a major component 32 and a minor component 34.

[0033] FIG. 3 is a cross-sectional view of a portion of a chemically patterned substrate 40. A polymer brush layer 42 is formed on a surface 44 of the substrate. In this example, openings 46, 48 are formed in the polymer brush layer. The substrate is formed of a material having an affinity to a first component of a block copolymer, and the polymer brush layer 42 is formed of a material having an affinity to a second component of the block copolymer. When the block copolymer is subsequently applied to the substrate, the positions of the domains of the block copolymer will be controlled by the affinities of the block copolymer components with the substrate and the polymer brush layer. The example of FIG. 3 includes a concave substrate pattern.

[0034] FIG. 4 is a cross-sectional view of a portion of a chemically patterned substrate 50. A polymer brush layer 52 is formed on a surface 54 of the substrate. In this example, nanoposts 56, 58 are formed on the polymer brush layer. The polymer brush layer is formed of a material having an affinity to a first component of a block copolymer, and the nanoposts are formed of a material having an affinity to a second component of the block copolymer. When the block copolymer is subsequently applied to the substrate, the positions of the domains of the block copolymer will be controlled by the affinities of the block copolymer components with the polymer brush layer and the nanoposts. The example of FIG. 4 includes a convex substrate pattern.

[0035] In the examples described herein, the polymer brush layer can be comprised of polystyrene (for copolymers with polystyrene as the major blocks). In the example of FIG. 4, the nanoposts can be comprised of  $\text{SiO}_x$  or various metals, such as tantalum, chromium, titanium, etc.

[0036] To form the pattern, a block copolymer can be deposited on the patterned surface via spin-coating from a dilute solution in general solvents like toluene, forming monolayered spheres (for sphere-form block copolymers) or lying-down cylinders (for cylinder-form block copolymers), and one domain of the block copolymer can be removed, using one of several known techniques, to leave a plurality of nanostructures in the form of dots (or holes) or lines (or trenches).

[0037] Block copolymer nanostructures can be used to form structures having half-pitch domain sizes in the order of about 5 nm to about 50 nm. However, these block copolymer nanostructures usually lack long-range order. In one aspect, this invention addresses the poor long-range order issue by using a substrate having a surface pattern with a chemical contrast to promote long-range order in block copolymer nanostructures.

[0038] The block copolymer can include two organic blocks (e.g., polystyrene-block-polymethylmethacrylate), or one organic block and one inorganic block (e.g., polystyrene-block-polydimethylsiloxane). One of the domains can be removed by UV degradation followed by a wet rinse. For example, upon UV exposure, polymethylmethacrylate is degraded while polystyrene is cross-linked. In another example, oxygen plasma can be used to remove organic components. Polydimethylsiloxane has good resistance to oxygen plasma.

[0039] The substrate pattern with chemical contrast and customized pattern layout can be used to direct the positioning of self-assembled nanodomains with domain periods of 25 nm or less ( $\geq 1 \text{ Tdot/in}^2$ ). This substrate chemical pattern can be generated by various advanced lithographic techniques, such as e-beam, nanoimprint, EUV, 193 nm, 248 nm, X-ray, etc. Although block copolymers are used as examples here, the self-assembled material is not limited to block copolymers, and it can be any self-assembling materials with at least two chemically distinct components, e.g., chemically functionalized nanoparticles and nanotubes. In a chemically functionalized nanoparticle, besides the organic nanoparticle inner core, there is an outer shell comprised of organic

polymer chains which have a distinct chemical property compared with the inner core. One example of a chemically functionalized nanoparticle is: 3-aminopropyl-(3-oxobutanoic acid) functionalized silica nanoparticle.

[0040] FIGs. 5, 6 and 7 are schematic representations of substrate dot patterns with various periodic lattice structures, where  $L_s$  is the period (i.e., the distance between alignment dots) in substrate pattern,  $L_{sx}$  is the period in an X direction, and  $L_{sy}$  is the period in a Y direction of a Cartesian co-ordinate system.

[0041] FIG. 5 shows a hexagon pattern of alignment dots positioned such that  $L_{sy} = 0.866L_{sx}$ . FIG. 6 shows a stagger pattern of alignment dots positioned such that  $L_{sy} = L_{sx}$ . FIG. 7 shows a square pattern of alignment dots positioned such that  $L_{sy} = L_{sx}$ .

[0042] The period of the substrate pattern is not necessarily equal to the domain period (1X) in a natural block copolymer pattern, which is helpful to release the pressure of conventional lithographic technology used to generate the substrate pattern, for example by e-beam lithography or optical lithography. The natural pattern of self-assembled materials refers to the self-assembled nanostructure formed without the guidance of external fields, such as a substrate topographic pattern or chemical contrast pattern. With a method described here, only a sparse substrate pattern (e.g., chemical contrast) needs to be generated by conventional lithography, which will be used to direct a dense self-assembled pattern. Thus, self-assembly releases the resolution pressure of conventional lithography.

[0043] The pattern multiplication (i.e., the ratio of substrate pattern period and block copolymer pattern period) ranges from about one to about 10. For example, the ratio of 10 can be used if a single grain of  $10 \times 10$  block copolymer domains can be typically formed in a natural block copolymer nanopattern without any surface guidance and thus in the form of multi-grain structures.

[0044] Such a pattern multiplication is useful for patterned media fabrication having an areal dots density of  $1\text{--}2 \text{ Tdot/in}^2$  and beyond. The patterning resolution of this method is only limited by the properties of available self-assembling materials, which have half-pitch dimensions of about 4 nm to about 50 nm for block copolymers, about 3

nm to about 10 nm for nanoparticles, and about 1 nm to about 5 nm for nanotubes, corresponding to areal densities of 1-50 Tdot/in<sup>2</sup>.

[0045] FIGs. 8, 9 and 10 are schematic representations of block copolymer patterns directed by periodic substrate patterns with same or different lattice structures.

[0046] FIG. 8 shows a pattern of nanostructures formed on a substrate having alignment dots at the positions indicated by item number 60. The alignment dots are positioned such that  $L_{sy} = 0.866L_{sx}$ . FIG. 8 shows a hexagonal pattern of alignment dots with 3 times (3X) multiplication, wherein  $L_s = nL_o(\pm 10\%)$ , for  $n = 1, 2, \dots, 10$ , and where  $L_o$  is the period in a natural (i.e., un-directed) block copolymer pattern. However, the pattern of alignment dots in FIG. 8 is not limited to a 3X multiplication.

[0047] FIG. 9 shows a pattern of nanostructures formed on a substrate having alignment dots at the positions indicated by item number 62. The alignment dots are positioned such that  $L_{sy} = L_{sx}$ . FIG. 9 shows a stagger pattern of alignment dots with 3X multiplication, wherein  $L_s = nL_o(\pm 10\%)$ , for  $n = 1, 2, \dots, 10$ . However, the pattern of alignment dots in FIG. 9 is not limited to a 3X multiplication.

[0048] FIG. 8 shows a pattern of nanostructures formed on a substrate having alignment dots at the positions indicated by item number 64. The alignment dots are positioned such that  $L_{sy} = L_{sx}$ .

[0049] FIG. 10 shows a square pattern of alignment dots with 4 times (4X) multiplication, wherein  $L_s = 2nL_o(\pm 10\%)$ , for  $n = 1, 2, \dots, 5$ . However, the pattern of alignment dots in FIG. 10 is not limited to a 3X multiplication.

[0050] In the structures of FIGs. 8, 9 and 10, a 10×10 natural lattice structure is assumed to be obtainable in a block copolymer pattern without any substrate guidance.

[0051] The lattice structure of the substrate pattern can also be different from that of naturally self-assembled structures. For example, substrate patterns with hexagon, stagger, or square array are all able to align block copolymer spherical/cylindrical domains with a naturally hexagon lattice. Furthermore, the substrate pattern need not be periodic, as long as it can direct long-range ordering of block copolymer domain structures by pinning some block copolymer nanodomains to the underlying substrate at some spots.

[0052] FIG. 11 is a schematic representation of a block copolymer pattern directed by a non-periodic substrate pattern having alignment dots at the positions indicated by item number 66. In this example, the average dimension for  $L_s$  is  $\langle L_s \rangle$ , and  $\langle L_s \rangle$  is in a range from about  $2L_o$  to about  $10L_o$ .

[0053] The substrate pattern can be created by optical lithography. A substrate having a chemical contrast surface can include alternating hydrophobic/hydrophilic regions or alternating polar/non-polar regions having a distinct affinity to distinct blocks in the copolymer.

[0054] Self-assembled nanodot arrays can be directed by a substrate chemical pattern with pattern pitches that are much larger than the pitches of the nanodot array. By using a carefully designed self-assembly system, a spherical block copolymer self-assembled on a substrate hexagon dot pattern with a low-topography chemical contrast, highly addressable block copolymer dot arrays with 24 nm pitch ( $1.3 \text{ Tdot/in}^2$ ) directed by substrate dot arrays with a periodicity of 24 nm/48 nm/72 nm/96 nm have been fabricated. In addition, directed  $>2 \text{ Tdot/in}^2$  dot arrays have also been successfully demonstrated. In this example, the dots are arranged in the array format of FIG. 5.

[0055] While others have studied perpendicularly oriented cylindrical block copolymers, a neutral surface wetting condition is required to achieve domain orientation perpendicular to both substrate/copolymer interface and copolymer/air interface in the case of cylindrical block copolymers. In one aspect, this invention includes a spherical block copolymer without the concern of neutral surface wetting to generate an addressable dot array, which is in thermodynamic equilibrium and thus intrinsically has a low defect density and long-term stability.

[0056] FIG. 12 is a photomicrograph of a portion of a patterned media in accordance with an aspect of the invention. FIG. 12 shows a  $1.3 \text{ Tdot/in}^2$  spherical PS-PDMS block copolymer pattern directed by a hexagon substrate pattern with 3X period.

[0057] FIG. 13 is a schematic cross-sectional view of a portion of a patterned media similar to that shown in FIG. 12. In the example of FIG. 13, a substrate 70 with a chemically contrasting surface 72 includes a polymer brush layer 74 and openings 76, 78 in the polymer brush layer. A block copolymer 80 is deposited on the chemically contrasting surface. The block copolymer includes a plurality of substantially spherical

domains 82, 84, 86 and 88 of a first component in a second component 90. Domains 82 and 88 have an affinity to the substrate and therefore form at the locations of the openings in the brush polymer layer.

[0058] FIG. 14 is a schematic cross-sectional view of the portion of the patterned media of FIG. 13, after the second component has been substantially removed.

[0059] In another aspect of the invention, by combining a substrate chemical pattern with a cylindrical block copolymer, highly ordered dense line patterns can be fabricated. FIG. 15 is a photomicrograph of a cylindrical poly(styrene-dimethyl siloxane) (PS-PDMS) block copolymer pattern directed by a substrate dot pattern. FIG. 15 shows a patterned portion 92 and an unpatterned portion 94, without an underlying substrate pattern. There is no obvious domain orientation in the unpatterned area.

[0060] The chemical contrast pattern on the substrate includes a plurality of dots 96 as shown in FIG. 16. In the pattern of FIG. 16,  $L_s = n\sqrt{3}L_o(\pm 10\%)$ , with  $n = 1, 2, \dots, 5$ , and where  $L_o$  is the period in natural (i.e., un-directed) block copolymer pattern. When a cylindrical block copolymer is deposited on the patterned surface, the cylinders attach to the pattern dots and lie in a direction substantially parallel to the patterned surface.

[0061] FIGs. 17, 18 and 19 are schematic representations of a cross-section of a patterned media constructed with a cylindrical block copolymer in accordance with an aspect of the invention.

[0062] FIG. 17 shows a cross-sectional schematic view in cross-track direction. In the example of FIG. 17, a substrate 100 with a chemically contrasting surface 102 includes a polymer brush layer 104 and openings 106 in the polymer brush layer. A cylindrical block copolymer 108 is deposited on the chemically contrasting surface. The block copolymer includes a plurality of substantially cylindrical domains 110, 112 and 114 of a first component in a second component 116. Domains 110 and 114 have an affinity to the substrate and therefore form at the locations of the openings in the brush polymer layer.

[0063] FIG. 18 is a schematic cross-sectional view of the portion of the patterned media of FIG. 17, after the second component has been substantially removed.

[0064] FIG. 19 is a cross-sectional schematic view of the structure of FIG. 18 in the down-track direction.

[0065] The block copolymer materials can be any spherical (for a dot array of nanostructures) or cylindrical (for a dot or line array of nanostructures) block copolymers with two (or more) highly immiscible blocks/components, A and B (or more), which can form nanostructures with domain spacings of 25 nm or less, such as polystyrene-polymethylmethacrylate (PS-PMMA) (down to ~20-25 nm), poly(styrene-dimethyl siloxane) (PS-PDMS) (down to ~10 nm), polystyrene-poly(ethylene oxide) (PS-PEO) (down to ~15 nm), PS-P2VP (down to ~12 nm), polystyrene-block-poly(4-vinylpyridine) (PS-P4VP) (down to ~15 nm), etc.

[0066] In one example, the block copolymer nanostructure can be directly used as a recording media if one component/block includes magnetic elements, such like cobalt, iron, etc.

[0067] The self-assembled nanodomains can be integrated into BPM nanoimprint template fabrication including both a regular bit pattern and a non-regular servo pattern as shown in FIG. 20.

[0068] FIG. 20 is a schematic representation of a data storage disc template 120 in accordance with an aspect of the invention. The disc template includes a plurality of tracks 122, only one of which is shown. Each track includes a plurality of data bit areas 124, and a plurality of servo areas 126. The data bit areas can be fabricated using the process described herein. The servo areas can be fabricated using a lithographic process, such as e-beam writing.

[0069] FIG. 21 is a process flow diagram illustrating a method for using directed self-assembled block copolymer nanostructures in BPM template fabrication including both a bit pattern and a servo pattern. In this method, e-beam writing (EBW) is used to generate a servo pattern in the servo area, and a self-assembly material/process is used to prepare a high-density dot array in the bit area. Block 130 shows that the method starts by coating a substrate with a thin polymer brush layer. In one example, the thin polymer brush layer can have a thickness of about 1 nm to about 10 nm.

[0070] The thin polymer brush layer is then coated with a photoresist layer having, for example, a thickness of about 20 nm to about 50 nm. The photoresist can be

patterned using known techniques to include a regular dot pattern (in a bit area) and a non-regular servo pattern (in a servo area). The photoresist can be patterned using, for example, e-beam lithography, optical lithography, etc. (block 132).

[0071] Next, a first evaporation and liftoff process can be used to form a first hard mask pattern in both the bit and servo areas (using for example, chromium, tantalum, etc.).

[0072] The regular dot pattern in the bit area will be used as a substrate pattern to guide a subsequently applied block copolymer pattern and the non-regular servo pattern in servo area will be used as final servo pattern (block 134).

[0073] Block 136 shows that the block copolymers are coated and annealed (e.g., via a thermal/solvent process) to form a highly ordered block copolymer pattern in the bit area directed by the hard mask dot pattern formed previously.

[0074] Block 138 shows that a second evaporation and liftoff process can be used to form a second hard mask pattern in the bit area, which may partially overlap with a first hard mask pattern in some spots.

[0075] Next, the final hard mask patterns, including a bit pattern (from the second hard mask pattern) and a servo pattern (from the first hard mask pattern) are transferred into the substrate (that may be quartz, for an ultraviolet (UV) imprint) by etching (or other methods), and all hard mask patterns can be removed by a wet etch, as shown in block 140.

[0076] The method illustrated in FIG. 21 can be integrated into the fabrication of BPM nanoimprint master templates including both a bit pattern (having a regular period, high pattern density, single shape, tight size/position sigma) and a server pattern (that can be non-periodic or periodic, with a moderate-to-high pattern density, flexible shape, etc.). A directed self-assembled pattern can be used for the bit region and an e-beam defined pattern can be used for server region.

[0077] The block copolymer can include two organic blocks (e.g., polystyrene-block-polymethylmethacrylate) or one organic block, one inorganic block (e.g., polystyrene-block-polydimethylsiloxane). One of the domains can be removed by UV degradation followed by a wet rinse. For example, upon UV exposure, polymethylmethacrylate is degraded while polystyrene is cross-linked. In another

example, oxygen plasma can be used to remove organic components in a hybrid organic-inorganic block copolymer. The inorganic block (i.e., polydimethylsiloxane) has good resistance to oxygen plasma.

[0078] In one example, spherical block copolymers are directed by a chemical contrast substrate pattern with a customized dot pattern layout to generate highly ordered dense dot arrays with ultra-high pattern densities.

[0079] In another example, cylindrical block copolymers are directed by a chemical contrast substrate pattern with a customized dot pattern layout to generate highly ordered line arrays with high pattern densities.

[0080] In one aspect, the highly ordered dot array generated by using the directed self-assembly method described above can be integrated with an e-beam lithography process to fabricate a full-disc BPM template including both a servo pattern and a bit pattern.

[0081] In another aspect, this invention provides apparatus fabricated using one of the described methods.

[0082] While the invention has been described in terms of several examples, it will be apparent to those skilled in the art that various changes can be made to the disclosed examples without departing from the scope of the invention as defined by the following claims. The implementations described above and other implementations are within the scope of the claims.

What is claimed is:

1. A method comprising:  
providing a substrate having a plurality of chemically contrasted alignment features; and  
depositing a self-assembled material on at least a portion of the substrate, wherein the position and/or orientation of substantially spherical domains of the self-assembled material is directed by the alignment features, to form a nanostructure pattern, and wherein the period of the alignment features is between about 2 times and about 10 times the period of the spherical domains.
2. The method of claim 1, wherein the alignment features are smaller than the spherical domains.
3. The method of claim 1, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = nL_o(\pm 10\%)$ , for  $n = 1, 2, \dots, 10$ .
4. The method of claim 1, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = n\sqrt{3}L_o(\pm 10\%)$ , with  $n = 1, 2, \dots, 5$ .
5. The method of claim 1, wherein the alignment features are positioned with an average period of  $\langle L_s \rangle$ , and the self-assembled material has a natural period of  $L_o$ , and  $\langle L_s \rangle$  is in a range from about  $2L_o$  to about  $10L_o$ .
6. An apparatus comprising:  
a substrate having a plurality of chemically contrasted alignment features; and  
a self-assembled material on at least a portion of the substrate, wherein the position and/or orientation of substantially spherical domains of the self-assembled material is directed by the alignment features, to form a nanostructure pattern, and wherein the average spacing of the alignment features is between about 2 times and about 10 times the period of the spherical domains.
7. The apparatus of claim 6, wherein the alignment features are smaller than the spherical domains.

8. The apparatus of claim 6, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = nL_o(\pm 10\%)$ , for  $n = 1, 2, \dots, 10$ .

9. The apparatus of claim 6, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = n\sqrt{3}L_o(\pm 10\%)$ , with  $n = 1, 2, \dots, 5$ .

10. The apparatus of claim 6, wherein the alignment features are positioned with an average period of  $\langle L_s \rangle$ , and the self-assembled material has a natural period of  $L_o$ , and  $\langle L_s \rangle$  is in a range from about  $2L_o$  to about  $10L_o$ .

11. A method comprising:

providing a substrate having a plurality of discrete chemically contrasted alignment features; and

depositing a self-assembled material on at least a portion of the plurality of chemically contrasted alignment features, wherein the position and/or orientation of substantially cylindrical domains of the self-assembled material is directed by the alignment features, to form a laminar pattern, and wherein the period of the alignment features is between about 2 times and about 10 times the period of the cylindrical domains.

12. The method of claim 11, wherein the alignment features are smaller than the cylindrical domains in at least one direction.

13. The method of claim 11, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = n\sqrt{3}L_o(\pm 10\%)$ , with  $n = 1, 2, \dots, 5$ .

14. An apparatus comprising:

a substrate having a plurality of discrete chemically contrasted alignment features; and

a self-assembled material on at least a portion of the plurality of chemically contrasted alignment features, wherein the position and/or orientation of substantially cylindrical domains of the self-assembled material is directed by the alignment features, to form a laminar pattern, and wherein the average spacing of the

alignment features is between about 2 times and about 10 times the period of the cylindrical domains.

15. The method of claim 14, wherein the alignment features are smaller than the cylindrical domains in at least one direction.

16. The method of claim 14, wherein the alignment features are positioned with a period of  $L_s$ , and the self-assembled material has a natural period of  $L_o$ , and  $L_s = n\sqrt{3}L_o(\pm 10\%)$ , with  $n = 1, 2, \dots, 5$ .

17. A method comprising:  
forming a first plurality of spaced dots in a servo area of a substrate;

using a lithographic process to form a second plurality of spaced dots in a bit area of a substrate; and

depositing a self-assembled material on at least a portion of the bit area, wherein the position and/or orientation of domains of the self-assembled material is directed by the second plurality of spaced dots, to form a nanostructure pattern in the bit area.

18. The method of claim 17, wherein the step of using a lithographic process to form a second plurality of spaced dots in a bit area of a substrate are implemented by coating a substrate with a polymer brush layer and patterning the polymer brush layer.

19. The method of claim 17, wherein the domains of the self-assembled material comprise spherical domains.

20. The method of claim 17, wherein the domains of the self-assembled material comprise cylindrical domains and the nanostructure pattern comprises a laminar pattern.