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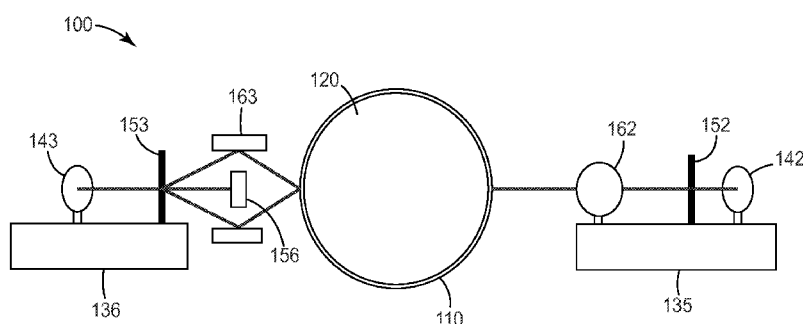


FIG. 2B

(57) Abstract: A method and system are provided for fabricating a replication tool having nanostructures formed thereon. The method includes patterning a substrate material having a photoresist coating layer. The substrate is disposed on a curved surface of a roll. The patterning comprises a dynamic interference lithography process. The patterned substrate is developed then etched, where the etching transfers the pattern from the photoresist coating to the underlying substrate. The replication tool can have nanometer-scale structures formed thereon, with feature sizes down to about 100 nm.

METHOD AND SYSTEM FOR FABRICATING NANOSTRUCTURE MASS REPLICATION TOOL

BACKGROUND

The present invention relates generally to manufacturing systems and methods.
5 More specifically, the present invention relates to a method and system for fabricating a tool used for mass replication of nanostructures.

The demand for new products with more features in smaller areas has resulted in an increasing demand to manufacture smaller features at higher yields. These features can be on the sub-micron or nanometer scale. Some conventional techniques for
10 manufacturing nanostructures of three dimensions (where such structures have length, height, and width features in the nanometer regime) are known. These conventional methods include techniques based on colloidal sedimentation, polymer phase separation, templated growth, fluidic self-assembly, multiple beam interference lithography, multiple exposures of two optical beams and methods based on printing, molding, and writing.
15 Such conventional techniques are also discussed in US Publication No. 2009-0162799-A1, incorporated by reference herein in its entirety.

In a conventional roll-to-roll replication process, a diamond turned master roll, drum or cylinder can be utilized. However, diamond turning can lead to feature size and shape limitations. In addition, once a metal replication master tool is machined, it is
20 difficult and expensive to alter the structured pattern in response to changing customer requirements.

Other conventional replication processes are described in US Patent Nos. 6,322,652 and 6,375,870.

SUMMARY

25 In one aspect of the present invention, a method for fabricating a replication tool having nanostructures formed thereon is provided. The method includes patterning a substrate material having a photoresist coating layer. The coated substrate is disposed on a curved surface of a roll and where the patterning comprises a dynamic interference lithography process. The patterned substrate is developed then etched, where the etching
30 transfers the pattern from the photoresist coating to the underlying substrate.

The above summary of the present invention is not intended to describe each illustrated embodiment or every implementation of the present invention. The figures and the detailed description that follows more particularly exemplify these embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Fig. 1 is flowchart showing an exemplary process for forming a replication tool according to an aspect of the invention.

 Figs. 2A and 2B are different schematic views of a dynamic interference lithography system according to another aspect of the invention.

 Figs. 3A and 3B are schematic views of a striping lithography technique according
10 to another aspect of the invention.

 Figs. 3C and 3D are schematic views of a stitching lithography technique according to another aspect of the invention.

 Fig. 4 is a schematic view of a resulting striping and stitching combination pattern according to another aspect of the invention.

15 Figs. 5A – 5C are SEM images of a first experimental patterned substrate.

 Fig. 6 is an SEM image of an experimental replication tool.

 Figs. 7A and 7B are AFM images of an experimental structure pattern and an experimental replica of that structure pattern, respectively.

 Fig. 8 is an SEM image of another experimental patterned substrate.

20 Fig. 9 is an SEM image of another experimental patterned substrate.

 Fig. 10 is an SEM image of another experimental patterned substrate.

 While the above-identified drawing figures set forth several embodiments of the invention, other embodiments are also contemplated, as noted in the discussion. In all cases, this disclosure presents the invention by way of representation and not limitation. It
25 should be understood that numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope of the principals of this invention. The figures may not be drawn to scale. Like reference numbers have been used throughout the figures to denote like parts.

DETAILED DESCRIPTION

30 The present invention relates to a method and system for making a durable tool for the mass replication of nanostructures. The tool is a flexible substrate having a pattern of

nanostructures formed thereon that can be replicated in a roll-to-roll manufacturing process. An exemplary process 10 for making the mass replication tool is shown with respect to the flowchart of Fig. 1.

In step 12, a substrate material is prepared (e.g., cleaned) and coated with a photoresist material. In one exemplary aspect, the substrate material is a flexible substrate, such as a film. In one aspect, the flexible substrate comprises a polymer-based material, such as a polyimide (PI) material or a polyethylenenaphthanate (PEN) material. These exemplary materials have strong absorption in the UV. In an alternative aspect, the substrate can further include materials that are deposited onto the polymer substrate.

These materials would then be disposed between the polymer substrate and the photoresist coating. These additional materials may be utilized for their etching characteristics, depending on the type of nanostructures to be formed. These additional interstitial materials can include one or more additional photoresist layers, an acrylic, diamond like glass (DLG) or diamond like carbon (DLC) materials. In a further alternative, the substrate can include metal foil materials, such as, stainless steel, other steels, aluminum, copper, metal clad polymer films, laminated materials, paper, or woven or nonwoven fabric materials. For all of the above substrate materials, they can further include a coated surface. In a further alternative, the substrate can comprise a material sleeve that conforms to the shape of the roll upon which the substrate is mounted.

In one aspect, the flexible substrate can have a width of about one or two inches up to several inches, and a length much longer than the width. For example, for practical mass replication applications, the substrate can have a width up to about 24 inches and a length up to about 96 inches. The substrate can preferably be used in a roll-to-roll process—thus a substrate with sufficient flexibility, that can be mounted onto the curved side of a roller in a straightforward manner, is preferred. Also, the size of the substrate can be appropriate to the size of the ultimate roller used in the replication process.

A photoresist coating is applied to the substrate via a conventional spin coating, spray coating, or web coating process. The photoresist material can be a conventional photoresist material, such as a Microposit™ MF™ S1805 photoresist (available from Rohm & Haas, Marlborough, MA) or an Ultra-i™ 123 i-line photoresist. The photoresist coating layer can have a thickness of about 100 nm to about 3 μm. A suitable thickness can depend on factors such as material type, exposure type, structure pitch size, and

exposure levels, as would be understood by one of skill in the art, given the present description.

In step 14, the prepared and coated flexible substrate is patterned. In a preferred aspect, the substrate is placed onto a roll or drum surface and patterned on the roll or drum
5 using a dynamic interference lithography technique. This exposure process creates a pattern of nanometer scale structures on the substrate. Details regarding the exemplary dynamic interference lithography technique are provided below.

In step 16, the patterned substrate is subjected to a conventional photoresist development process. For example, the substrate can be developed in a conventional
10 development solution, such as a Microposit™ MF™ CD-26 and Microposit™ MF™ 319 (aqueous alkaline tetramethyl ammonium hydroxide). In addition, in another aspect, depending on the photoresist used, a post-exposure baking process can be employed. In the (optional) post exposure bake, the substrate can be heated to a temperature of about 90°C to about 120°C. This post-exposure baking process can complete the cross-linking
15 of the photoresist, which was initiated by exposure to an appropriate wavelength of light.

The developed substrate is then etched in step 18. In one aspect, the substrate can be placed onto a roll or drum and subjected to a dry etching process in a plasma chamber. Alternatively, the substrate can be removed from the drum and etched as a flat substrate using a conventional etching technique. In this aspect, an RIE process is utilized to
20 transfer the pattern from the photoresist to the underlying substrate. An exemplary RIE process can be suitable for use in this step of the invention and can be performed in etching chamber 190, described below with respect to Fig. 2C. In one aspect, the selectivity between the photoresist and the substrate (e.g., a PI or PEN film) can be about 1:1 – therefore photoresist patterns can be (almost) identically transferred into the
25 substrate. Example nanostructure patterns are shown and described in the Experiment Section below.

In step 20, the residual photoresist is removed by a conventional solution, such as a photoresist developer or acetone. At this stage, the tool is complete and can be used in a replication process.

30 Optionally, in a further step 22, prior to the replication process, a release layer can be deposited onto the structured surface of the substrate. The release layer can reduce the surface energy, thereby allowing the replica to be easily peeled off during a replication

process. For example, a relatively thin release layer of a thickness of about 50 nm or less can be deposited via a PECVD process. In this example, the release layer can comprise, for example, TMS (tetramethylsilane), or a fluorosilane release agent such as, fluorinated siloxane. Alternatively, a hexafluoropolypropylene oxide derivative such as that disclosed
5 in U.S. Pat. No. 7,173,778, incorporated by reference herein in its entirety, can be utilized. The release layer deposition process can be performed as is disclosed in, for example, U.S. Pat. No. 6,696,157, incorporated by reference herein in its entirety.

Optionally, a conventional roll-to-roll replication process can be performed in step 24. In this step, the patterned substrate can be placed (e.g., with adhesive or vacuum
10 chuck) onto the outer cylindrical surface of a master roll or drum. Thus, the process of the present invention offers an alternative to utilizing a diamond-turned master roll.

As mentioned above, in one aspect, the coated flexible substrate is placed on a roll or drum and is patterned using a dynamic interference lithography technique. Figs. 2A and 2B show an exemplary dynamic interference lithography system 100.

15 Lithography system 100 includes a laser source 130 that is directed to one or both arms 102, 104 of the system by a beam splitter 106 to produce a nanostructure pattern on a substrate 110 that is disposed on an outer surface 123 of a roll or drum 120. The roll or drum 120 rotates about axis 122 via a rotary stage (not shown). The laser source can be any conventional laser, usually a UV laser, such as an Argon laser operating at 351 nm,
20 depending on the optical characteristics of the polymer substrate and photoresist selected.

The first arm 102 of system 100 includes a first Talbot-type interferometer comprising interferometer mirrors 162 and a phase mask 152 to produce an interference pattern on the substrate 110. A beam stop 155 is also provided. The input beam is shaped by beam shaping optics 142. In particular, these components are disposed on a motion
25 stage 135 (e.g., a linear stage) in order to produce a striping pattern (see Figs. 3A and 3B) on the substrate 110.

The second arm 104 of system 100 also includes a second Talbot-type interferometer comprising interferometer mirrors 163 and a phase mask 153 to produce an interference pattern on the substrate 110. The input beam is shaped by beam shaping
30 optics 143. A beam stop 156 is also provided. The second arm is configured to produce a stitching pattern (see Figs. 3C and 3D) on the substrate 110. As such, the beam shaping optics 143, mirror 161b, and phase mask 153 are disposed on a motion stage 136.

However, the interferometer mirrors 163 of the second Talbot-type interferometer are fixed in relation to the components disposed on motion stage 136. This configuration can allow the fringe pattern formed by the second Talbot-type interferometer to be more stable. This configuration also minimizes the potential for pitch, yaw, and roll errors.

5 This configuration can also be utilized to pattern flat substrates, as well as substrates that are drum or roll-mounted.

In an alternative aspect, the coated substrate can be patterned using a projection lithographic technique.

In general, interference lithography utilizes an interferometer, such as a Talbot
10 interferometer, which produces two interfering laser beams that form a periodic interference pattern. The spacing, Λ , of the interference pattern is given by:

$$\Lambda = \lambda / 2 \sin \theta$$

where λ is the laser wavelength, and θ is the intersection angle between the two beams at the sample. Λ can vary from 200 nm to tens of microns. In an exemplary aspect, during
15 patterning, the spacing is set to 500 nm. By using stable laser sources and optical mounts, the spacing (Λ) accuracy can be maintained in pico meters (i.e. 500 ± 0.5 nm). The size of the pattern is limited by the size of the beam, which typically can vary from tens of micrometers to millimeters. In a preferred aspect of the invention, a small beam is typically moved with respect to the surface of a substrate being patterned to pattern the
20 whole surface of the roll-mounted substrate. To decrease positional errors in the patterning process, the roll-mounted substrate is rotated while optics can be translated using air bearing stages and high resolution encoders in the stages.

Based on the relation between the direction of the rotary stage movement and the interference pattern orientation, there are three primary types of interference lithography
25 techniques for patterning a roll-mounted substrate – a striping technique (where fringes formed by the laser pattern are oriented perpendicular to the rotation axis, as is shown in Figs. 3A and 3B), a stitching/cascading technique (where fringes formed by the laser pattern are oriented along the rotation axis, as is shown in Figs. 3C and 3D), and a combination of the striping and stitching. In alternative aspects, multiple striping and/or
30 stitching techniques may be used to pattern a roll-mounted substrate.

As shown in Figs. 2A and 2B, the system 100 includes three motion stages – the two linear stages 135, 136 that carry the striping and stitching optics and a rotary stage (drum or roll 120) that rotates about axis 122. Since the interference patterns formed have sub-micron dimensions and require very precise alignment, in one aspect, both the linear and rotary stages ride on air bearings to minimize vibrations and stage motion errors such as pitch, yaw and roll.

In an alternative embodiment, the optics for striping and stitching can be placed on a single linear stage. In a further alternative, the patterning process 14 described herein can also be applied if the optics are stationary and the substrate is linearly translated while being rotated. In this alternative, the rotary stage and the roll 120 can be mounted on the linear stage.

Utilizing an exemplary Ar laser source for the experiments described in further detail below, the typical size of the beam at the substrate can be about 200 microns, with a fringe spacing of 500 nm.

In one aspect, to cascade the small interference pattern across the roll-mounted substrate, the optics, including the Talbot-type interferometer, can be translated across the roll-mounted substrate. The two interfering laser beams of the Talbot-type interferometer intersect at the surface of the coated substrate. In order to maintain good fringe visibility, the exposure pattern can be centered on the roll-mounted substrate throughout the writing process. The visibility of the interference pattern is typically defined by Fringe Visibility (FV) as:

$$FV = 100(I_{\max} - I_{\min}) / (I_{\max} + I_{\min}) \%$$

Since the typical size of the exposure pattern is less than 200 microns, its position can be maintained across the roll-mounted substrate with micron-scale accuracies to minimize wash out effects. If the drum or roll is not a perfect cylinder or the motion stages have errors or tilt with respect to each other, these errors can also result in the exposure pattern moving in and out with respect to the coated substrate surface. Accordingly, to reduce the misplacement errors, the rotary and linear stages can be well-aligned with respect to each other.

In addition, during patterning, it can be useful to have the tilt of the fringes aligned with the rotary stage motion. The tilt of the fringes is defined by the phase mask 152 and the interferometer mirrors 162. If the fringes are tilted with respect to the rotary axis 122,

it can decrease the contrast of the patterns. When there is no tilt error, a high fringe visibility (FV) is achievable. The phase mask and the surface of the drum/coated substrate are preferably set perpendicular to the laser beam. This can be verified by monitoring the back reflections from each surface. The position of the phase mask can be set to sub-

5 milliradian accuracy to minimize the wash out of the fringes during the exposure process.

As is show schematically in Fig. 3A, as the drum or roll 120 rotates, the striping pattern 125a is written onto the coated substrate 110. The linear stage 135 is moved across the substrate as it is rotated on the rotating drum or roll during the exposure to create a growing stripe pattern 125b, as is shown in Fig. 3B. Thus, the striping pattern can be

10 written across the entire width of the substrate 110 in this manner.

In addition, the use of a rotary motion to write the patterns allows for rapid movement of the substrate and rapid writing. As the rotary stage is turning, the linear stage translates in synchronization. For each turn of the rotary stage, the linear stage travels a distance equal to an integer multiple of the fringe spacing formed by the Talbot

15 interferometer. In other words, for any point on the wheel, multiple exposures take place as the wheel is turning. The number and duration of the exposures depends on the beam size and how fast the linear stage is translating. As an example, if the size of the beam is about 200 microns and the rotary and the linear stage speeds are 180 RPM and 40 micron/sec respectively, each exposure takes much less than a millisecond and each point

20 is exposed tens of times during a time of about 5 seconds. Total elapsed times can be even further decreased with higher rotation speeds and a different sized beam. As long as the fringe position is stable over this time it is not necessary to correct for motion of the fringes with respect to the substrate.

As mentioned above, an encoder arm can be optionally employed to sense the drift

25 of the fringes and positional errors caused by the linear stage(s). Such an encoder arm can be utilized as is described in US Patent No. 7,085,450, incorporated by reference herein in its entirety. A computer can be used as a controller. The linear and rotary stages are can be controlled by a conventional controller, such as a commercially available UMAC motion controller.

30 For striping operations, the rotary stage can be set to turn at a desired rate, typically over 150 RPM, while the linear stage position can be kept at:

$$\text{Linear Stage position} = \text{LSP}_0 + (\text{Rotary position} - \text{RSP}_0) * \text{Fringes to step per turn}$$

LSP₀ and RSP₀ is the initial position of linear and rotary stages respectively. Fringes to step per turn dictates how many averages takes place during the patterning process and patterning speed. As observed, larger averages result in more uniform pattern at the expense of increasing the time that it takes to pattern the entire roll-mounted
5 substrate.

Other errors and drift of the UV interference pattern can be controlled by using a piezoelectric drive coupled to the phase mask or one of the interferometer mirrors, where:

$$\text{Fringe Position} = (\text{Rotary position} - \text{RSP}_0) * \text{Fringes to step per turn}$$

One or more control loops can also be employed, especially for a manufacturing
10 setting. For example, a first control loop can be independently controlled and does not have any cross talk to a second control loop. However, once the second loop is enabled, the second control loop can detect any position errors caused by the control of the linear and rotary stages. It is possible to minimize some of the exposure pattern drift and stage errors (i.e. using stable mountings and high resolution encoders) in a well controlled lab
15 environment.

As mentioned above, another type of interference lithography technique for patterning a roll-mounted substrate is a stitching (or cascading) technique, where fringes are formed by the laser pattern and are oriented along the rotation axis, as is shown in Figs. 3C and 3D. As the drum or roll 120 rotates, the stitching pattern 126a is written onto
20 the coated substrate 110. The linear stage 136 is moved transversely across the width of the substrate 110 during the exposure to create an expanded stitching pattern 126b. Thus, the stitching pattern can be written across the entire width of the substrate 110 in this manner.

In more detail, for stitching/cascading writing, the rotary stage movement and the
25 interferometer are perpendicular to each other as is evident from Figs. 2A and 2B, where the second arm 104 of the system 100 performs the stitching operation. In this patterning technique, the interference fringes are transverse to the linear stage movement direction. As the roll-mounted substrate rotates, each spot on the substrate will be going through interference patterns. If the exposure is continuous or the laser is kept on as the substrate
30 rotates, the interference fringe pattern may be all washed out. To prevent this wash out effect from detrimentally impacting the patterning process, a stitching approach is utilized.

In this approach, the laser can be turned on only at predefined positions. In this way, each exposure can be in phase with the previous exposures.

In one aspect, in the stitching technique the speed of rotating substrate can be accurately maintained with respect to the fringes. This accuracy can be improved with the
5 use of high resolution rotary encoders and controllers, and furthermore employs the inertia of the rotary system and air bearing system to reduce external perturbations and frictions. Such an approach can be utilized as is described in US Patent No. 6,404,956, incorporated by reference herein in its entirety.

It is also advantageous to ensure that the interferometer mirrors are well aligned
10 with the phase mask for writing accuracy during stitching. This arrangement can provide an advantage of stable fringe patterns during the writing process. The laser can be modulated based on the rotary stage position in real time while the beam is translated by the linear stage 136. The size of the beam can be set to 200 micron as in the case of striping procedure described above. The linear stage translates the beam across the roll-
15 mounted substrate. The speed of the stage or the distance it travels is defined by how many averages or exposures it will take for each point on the roll. The positioning errors of the linear stage can be as much as tens of microns without having substantial negative impact on fringe visibility of the system.

In one aspect, an air bearing stage can be used in the stitching procedure to have
20 very smooth motion without having errors due to the pitch, yaw and roll of the stage that can lead to alignment problems of the beams. For a manufacturing environment, the fringe position of the interference pattern can be controlled via a control loop, such as described in US Patent No. 7,085,450, incorporated by reference above. As in the striping method, the encoder arm beam can be derived from the original laser beam.

As mentioned above, a third type of interference lithography technique for
25 patterning a roll-mounted substrate is a combination of the striping technique and the stitching technique. In one aspect, the striping technique is performed first, followed by the stitching technique. In another aspect, the stitching technique is performed first, followed by the striping technique. In another aspect, the striping and stitching techniques
30 are performed at the same time. The resulting periodic structures of the combination of patterning techniques can vary, in terms of thickness, height, or pitch at different locations on the substrate, and the physical characteristics of these structures can depend on the FV

of the overall lithography system. These types of structures are advantageous for mass replication. Fig. 4 shows a schematic representation of a combination patterning, and the Experiment section below shows actual patterns formed by a combination of the striping and stitching techniques described herein.

5 In a further alternative aspect, the substrate can be patterned (either by a striping or a stitching technique), then the substrate can be temporarily removed and rotated 90 deg., then remounted on the roll and patterned again using the same technique. In this manner, the dynamic interference lithography system need not include two separate writing arms.

10 Fig. 2C shows an exemplary embodiment of a suitable etching chamber 190. As mentioned above, the developed substrate is etched in step 18 (Fig. 1). An exemplary RIE process can be performed on roll-mounted substrate 110 in a reaction/etching chamber 190. Note that the chamber 190 may also be utilized for plasma deposition as well.

15 The etching chamber 190 includes a powered electrode 193 disposed on the roll 120 and a grounded electrode 194 disposed on the reaction chamber 190, which has a surface area greater than that of powered electrode 193. The cylindrical conductive roll 120 thus serves as the radio frequency (RF) powered electrode. The substrate 110 is mounted on the roll 120 which in turn is mounted in the chamber on a spindle (not shown). In the exemplary embodiment shown in Fig. 2C, the spindle and cylindrical conductive roll 120 remain stationary during etching.

20 Reaction chamber 190 can be evacuated to remove most air using vacuum pumps at a pumping stack (not shown) connected to the chamber 190. Aluminum is a preferred chamber material because it has a low sputter yield, which means that very little contamination occurs from the chamber surfaces. However, other suitable materials, such as graphite, copper, glass or stainless steel, may be used.

25 It will be noted that chamber 190 can utilize conventional means of providing a controlled environment that is capable of evacuation, containment of gas introduced after evacuation, plasma creation from the gas, and ion acceleration. In one aspect, chamber 190 has outer walls that are constructed in a manner sufficient to allow for evacuation of the interior chamber and for containment of a fluid for plasma creation and ion
30 acceleration.

 The desired process gases are supplied from storage through an inlet tube running around the inside of the chamber. A stream of gas is distributed throughout the chamber,

as illustrated by flow arrows 191a-191d (greater or fewer gas inlets can also be provided). In an exemplary embodiment, the inlet tube can be perforated to aide in the even distribution of gas in the chamber. Chamber 190 is closed and partially evacuated to the extent necessary.

5 Plasma is generated and sustained by means of a RF power supply (an RF generator operating at a frequency in the range of 0.001 to 100 MHz). To obtain efficient power coupling (i.e., wherein the reflected power is a small fraction of the incident power), the impedance of the plasma load can be matched to the power supply by means of matching network including two variable capacitors and an inductor. A description of
10 such networks can be found in Brian Chapman, *Glow Discharge Processes*, 153 (John Wiley & Sons, New York 1980).

The RF power supply powers the electrode (i.e. the cylindrical conductive roll 120) with a typical frequency in the range of 0.01 to 50 MHz. Upon application of RF power to the electrode, the plasma is established. In an RF plasma, the powered electrode becomes
15 negatively biased relative to the plasma. This bias is generally in the range of 100 to 200 volts. This biasing causes ions within the carbon-rich plasma to accelerate toward the electrode to form an ion sheath 192. The depth of the ion sheath 192 can range from approximately 1 mm (or less) to 50 mm and depends on the type and concentration of gas used, pressure applied, and relative size of the electrodes.

20 Thus, the process and system described herein is advantageous in that it is scalable and can yield a large area fabrication tool for mass replication applications. In particular, a replication tool having nanometer-scale structures, for example, feature sizes down to about 100 nm, with a height of up to 1000 nm, can be provided. Moreover, the process described herein allows the use of conventional coating and development techniques used
25 for flat substrates and further utilizes a patterning process on a cylindrical surface, which can be a faster process relative to a conventional flat patterning process.

Experiment

In a first experiment, an array of post or pole structures was formed using the exemplary process described herein. Figs. 5A-5C show SEM images (at different
30 magnifications and/or angles) of periodic post structures made on a photoresist-coated Microposit™ MF™ S1805 photoresist from Rohm & Haas, with a coating thickness of about 500 nm) PI polymer substrate (having a width of 4 inches) mounted on 14 inch

diameter roll. The patterning technique utilized was a combination of stitching and striping techniques consistent with those described above. In this experiment, for striping patterning, the beam size was about 50 μm x 120 μm , the rotary stage speed was about 120 RPM, and the linear stage moved at a rate of about 1.4 mm/min; for the stitching
5 writing, the beam size was about 175 μm x 150 μm , the rotary stage speed was about 12 RPM, and the linear stage moved at a rate of about 1.2 mm/min. After exposure, the film was removed from the roll and developed in a developing solution (Microposit™ MFT™ 319 developer, available from Rohm & Haas). In this experiment, the pitch was set to 500 nm. The height of the posts was about 300 nm. The duty cycle sampled at different
10 places on the substrate and varied between 30% to 40% across the roll based on the exposure conditions. The resulting structures had an average height of about 250 nm.

These structures were then etched in plasma etching chamber, using an oxygen etch. As the selectivity between the PI substrate and the photoresist is about 1:1, the patterns were successfully transferred to the PI substrate. An image of the structures
15 formed on the resulting tool is shown in Fig. 6. The resulting structures are prism-shaped, having a vertical wall at about 40° relative to the base. The investigators note that since the mounting roll was not perfectly concentric, eccentricity effects caused slightly different structure heights at different locations. In addition, it was observed that laser fluence inconsistencies can also lead to physical differences in the formed structures.

In general, for a combined patterning process, the patterning conditions become more stringent, as patterning errors can be amplified at doubly exposed areas of the substrate. These errors may cause a wash-out effect which reduces the patterns' height eventually to zero as the laser intensity increases. Accordingly, the error-reduction techniques described above can make the combined stitching and striping patterning more
20 efficient.

In another experiment, the patterned tool described above was tested for replication. In this experiment, the above described tool was coated with a release coating (a tetramethylsilane ("TMS") coating), then a UV curable acrylate coating was applied thereon. A PEN film was pressed onto the acrylate-coated tool. After a blanket exposure
30 by a UV lamp, a copy of the tool patterns was formed in the cured acrylate. The PEN film was peeled off the tool in a straightforward manner. Fig. 7A shows an image of the original pattern, while Fig. 7B shows an image of the replica.

In another experiment, a structured tool was formed using the following substrate—a polymer film, a first (durable) material layer (here, a chemically amplified epoxy-based negative photoresist, e.g., an Su-8 photoresist available from Michrochem, Newton, MA, having a thickness of about 3 μm) formed thereon, a DLG material layer (having a thickness of about 400 nm) deposited on the first material layer, and a photoresist layer (here, a S1805 photoresist material having a thickness of about 500 nm) coated on the DLG layer. The substrate was patterned using a combination of stitching and striping techniques consistent with those described above. The patterned photoresist layer was developed. The first photoresist pattern was transferred into the DLG using a C_3F_8 etch. An oxygen etch was used to transfer the patterns from the DLG (etch mask) to the durable material Su-8. These materials have a selective etch ratio of greater than 10, so the walls formed on the structures are sharp. Fig. 8 shows an SEM image of the resulting structures. This experiment shows that having properly selected multiple layers coated on substrate can increase the transferred aspect ratio. In this experiment, the sharpness of the vertical wall was improved, where the resulting structures had side wall angles of about 80° . In another version of this experiment, a structured tool was formed using a substrate that did not include the Su-8 photoresist, wherein the DLG material layer was deposited directly onto a polymer film.

In another set of experiments, structured tools were formed in accordance with the method described above. In these experiments, a photoresist with a non-linear response to a UV exposure was utilized. The nonlinear photoresist was an ultra i-123 photoresist (available from Rohm & Haas) and was coated onto a PEN film and a PI film. The patterning was accomplished using a combination of stitching and striping techniques consistent with those described above. After development, an image of the resulting pattern on the PEN film is shown in Fig. 9. These photoresist patterns can be further transferred into the underlying polymer substrate through etching, in this example, oxygen etching. An image of the resulting pattern on the PI tool is shown in Fig. 10. The use of a nonlinear photoresist can also provide a sharper wall angle, without the need for a multilayer coating on the substrate.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the scope of the invention.

We Claim:

1. A method of fabricating a tool having nanostructures formed thereon, comprising:
 - patterning a substrate coated with a photoresist coating layer, wherein the substrate
 - 5 is disposed on a curved surface of a roll and wherein the patterning comprises a dynamic interference lithography process;
 - developing the patterned substrate; and
 - etching the developed substrate to transfer the pattern from the photoresist coating to the underlying substrate.
- 10 2. The method of claim 1, further comprising:
 - removing the residual photoresist after the etching.
3. The method of claim 1, further comprising:
 - depositing a release layer on the patterned substrate.
4. The method of claim 1, wherein the substrate comprises a flexible polymer film
- 15 layer.
5. The method of claim 4, wherein the substrate comprises one or more materials disposed between the polymer film layer and the photoresist coating.
6. The method of claim 1, wherein the patterning comprises at least one of performing a striping technique, wherein fringes formed by an exposure pattern are
- 20 oriented perpendicular to the rotation axis of the roll, performing a stitching technique, wherein fringes formed by an exposure pattern are oriented along the rotation axis of the roll, and performing a combination of the striping and stitching techniques.
7. The method of claim 1, wherein the patterning comprises at least one of a striping technique and a stitching technique.
- 25 8. The method of claim 1, wherein patterning step includes patterning the substrate with a dynamic interference lithography system, the dynamic interference lithography system including at least one Talbot-type interferometer.

9. The method of claim 8, wherein the Talbot-type interferometer includes a set of interferometer mirrors and a phase mask.

10. The method of claim 9, wherein the interferometer mirrors are held stationary and the phase mask is translated during patterning.

5 11. A method of fabricating a tool having nanostructures formed thereon, comprising:
patterning a substrate coated with a photoresist coating layer and having a DLG
material disposed therebetween, wherein the substrate is disposed on a curved surface of a
roll and wherein the patterning comprises a dynamic interference lithography process;
developing the patterned photoresist coating material;
10 etching the DLG material layer to form a patterned DLG etch mask; and
etching the substrate with the DLG etch mask.

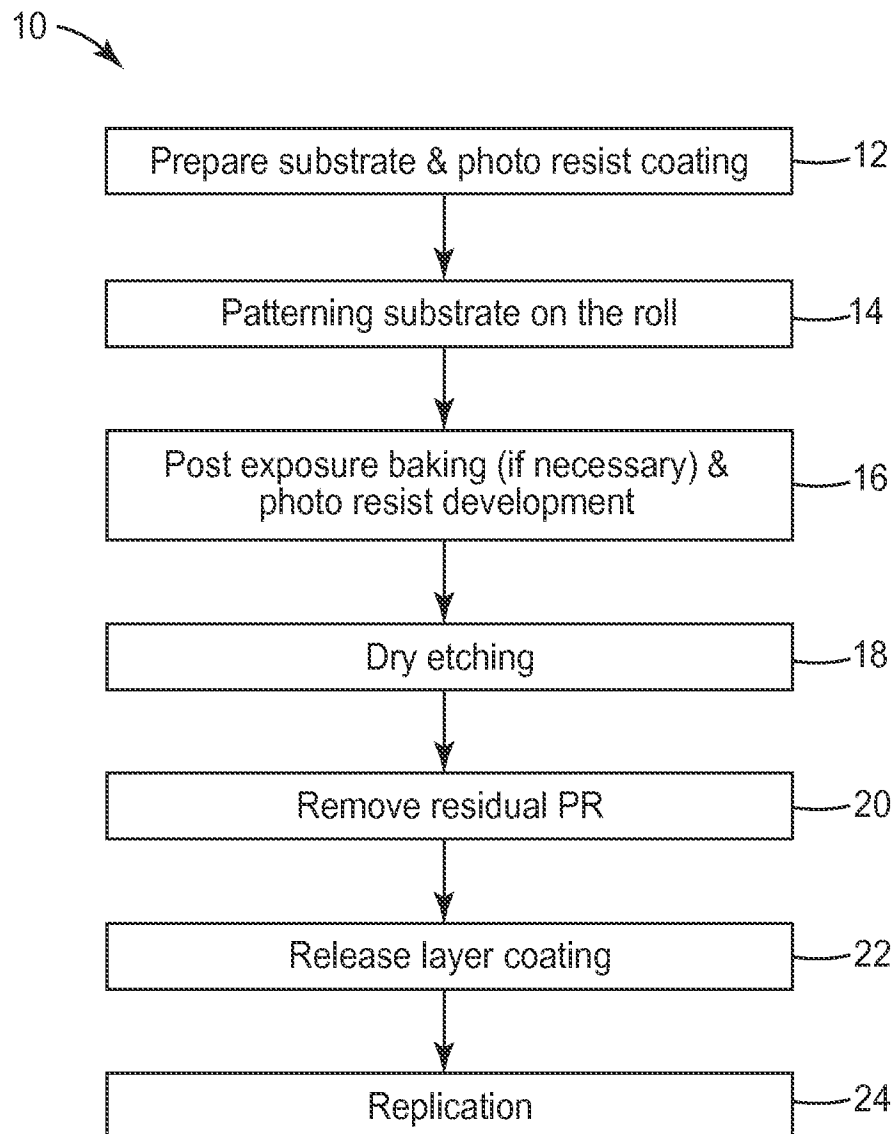
12. The method of claim 11, wherein the substrate is selected from the group
consisting of: a polymer-based material, a metal foil, a metal clad polymer film, a
laminated material, paper, a woven fabric, and a nonwoven fabric.

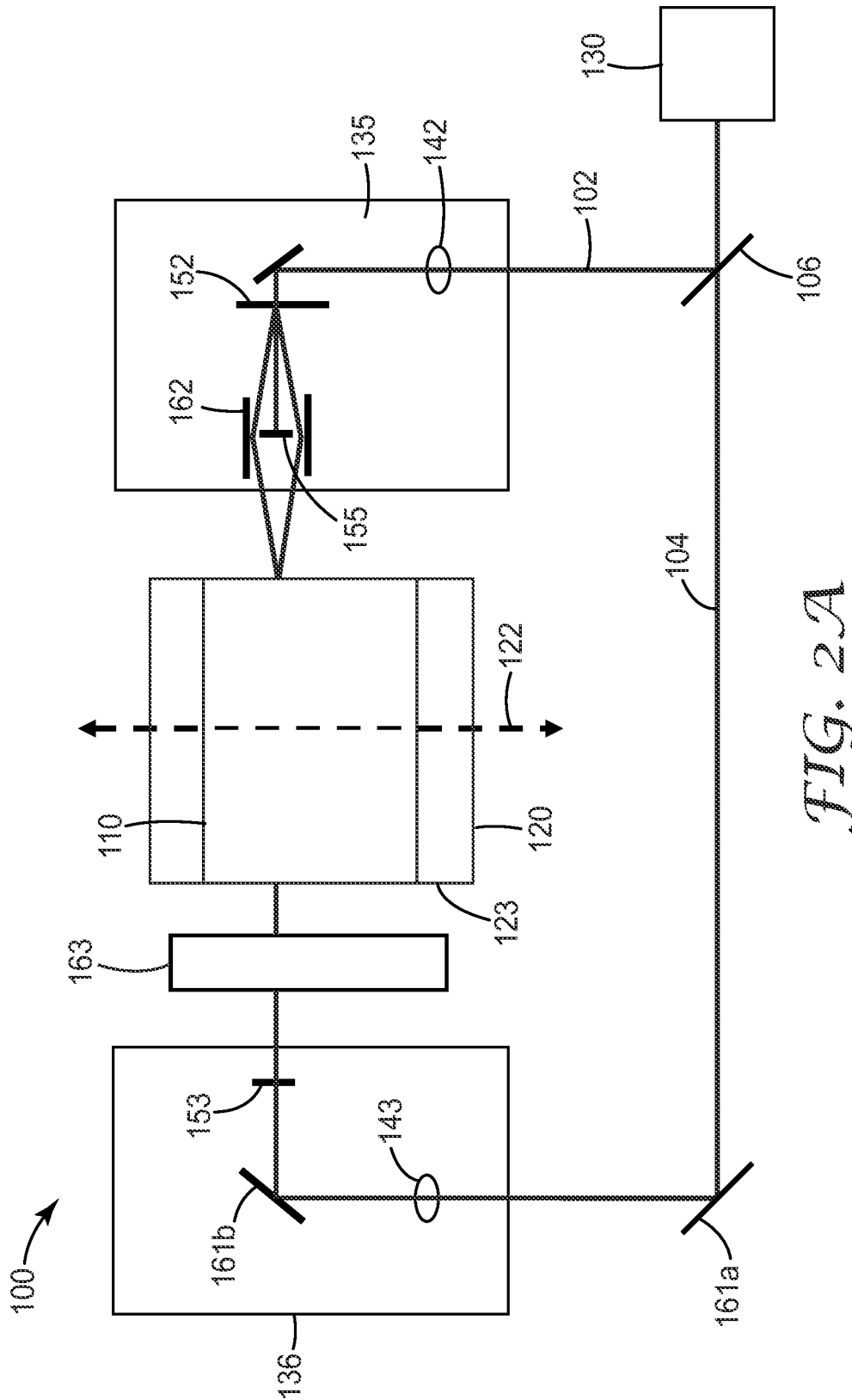
15 13. A replication process comprising,
forming replicas on a material with the tool fabricated by the method of claim 1.

14. A dynamic interferometer system, comprising:
a laser source to generate a light beam;
beam shaping optics to shape the light beam;
20 a phase mask disposed in the shaped beam path,;
a Talbot-type interferometer comprising a set of interferometer mirrors to receive
the beam and produce an interference pattern; and
a substrate disposed in the path of the interference pattern, wherein the phase mask
is mounted on a linearly movable stage, and wherein the interferometer mirrors are fixed
25 in relation to the phase mask during patterning of the substrate.

15. The dynamic interferometer system of claim 14, wherein the substrate is mounted
on a curved surface of a roll rotatably mounted on a rotary stage.

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*FIG. 1*



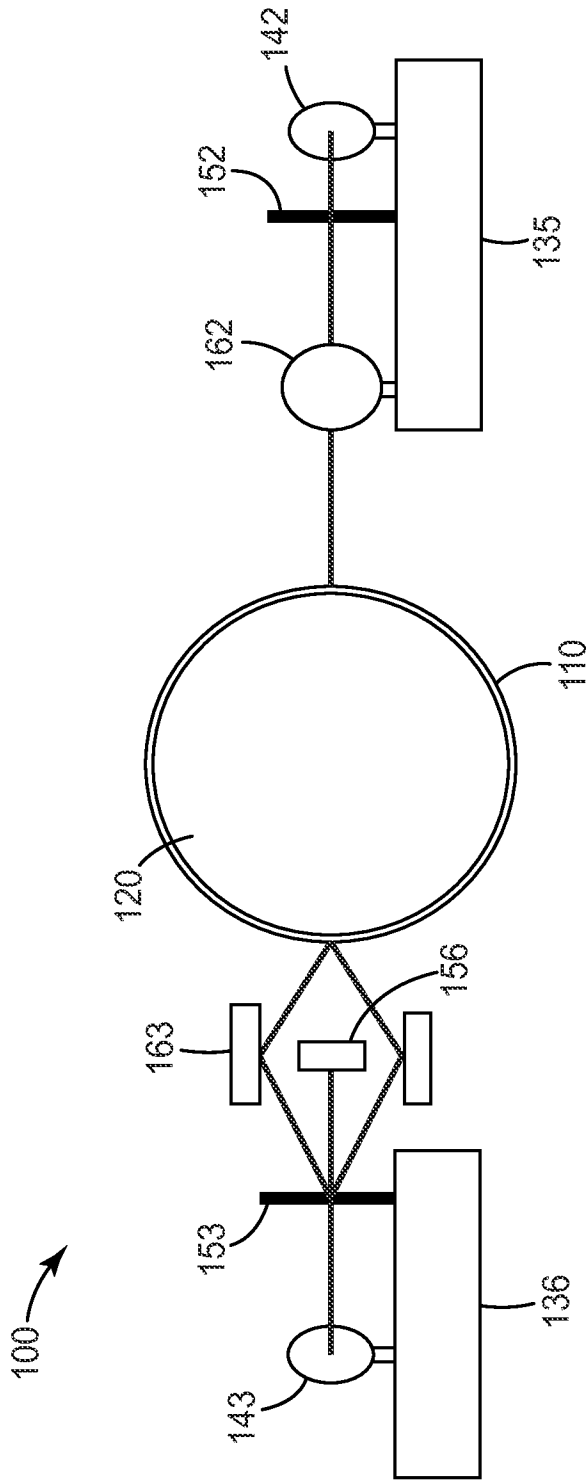
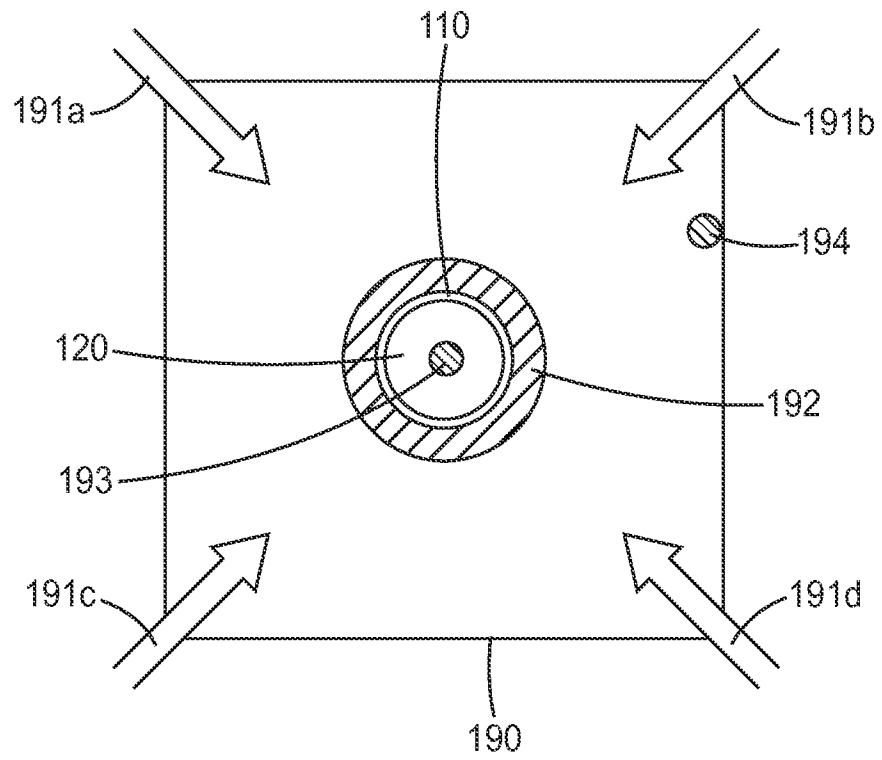


FIG. 2B

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*FIG. 2C*

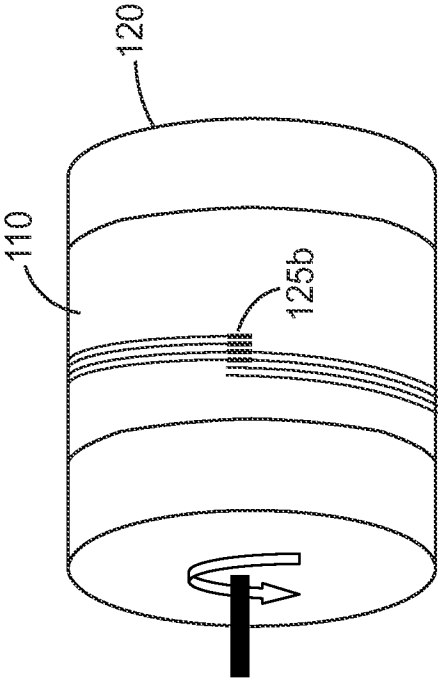


FIG. 3B

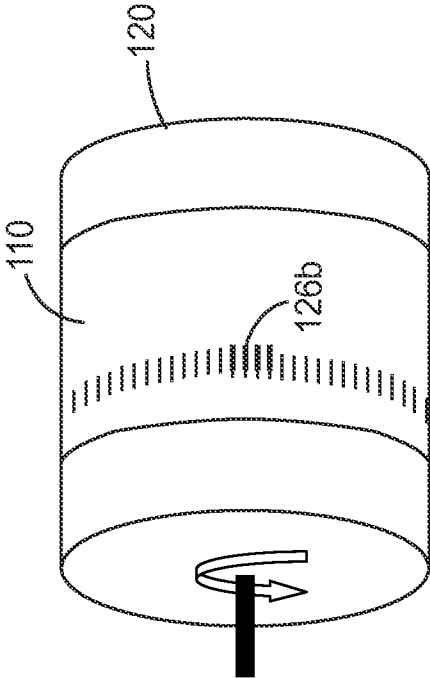


FIG. 3D

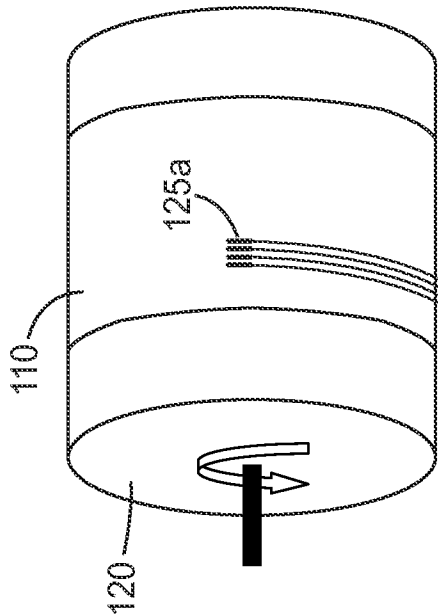


FIG. 3A

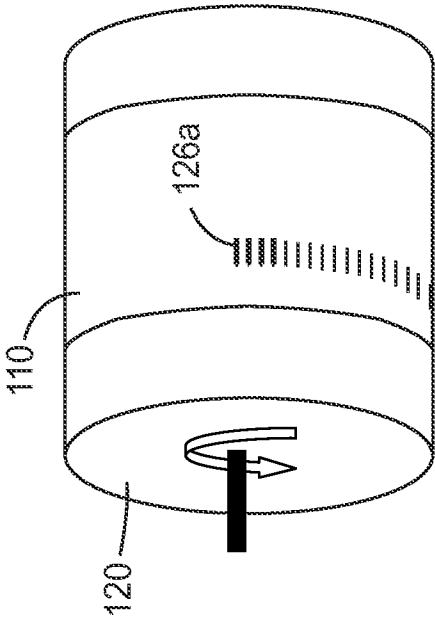
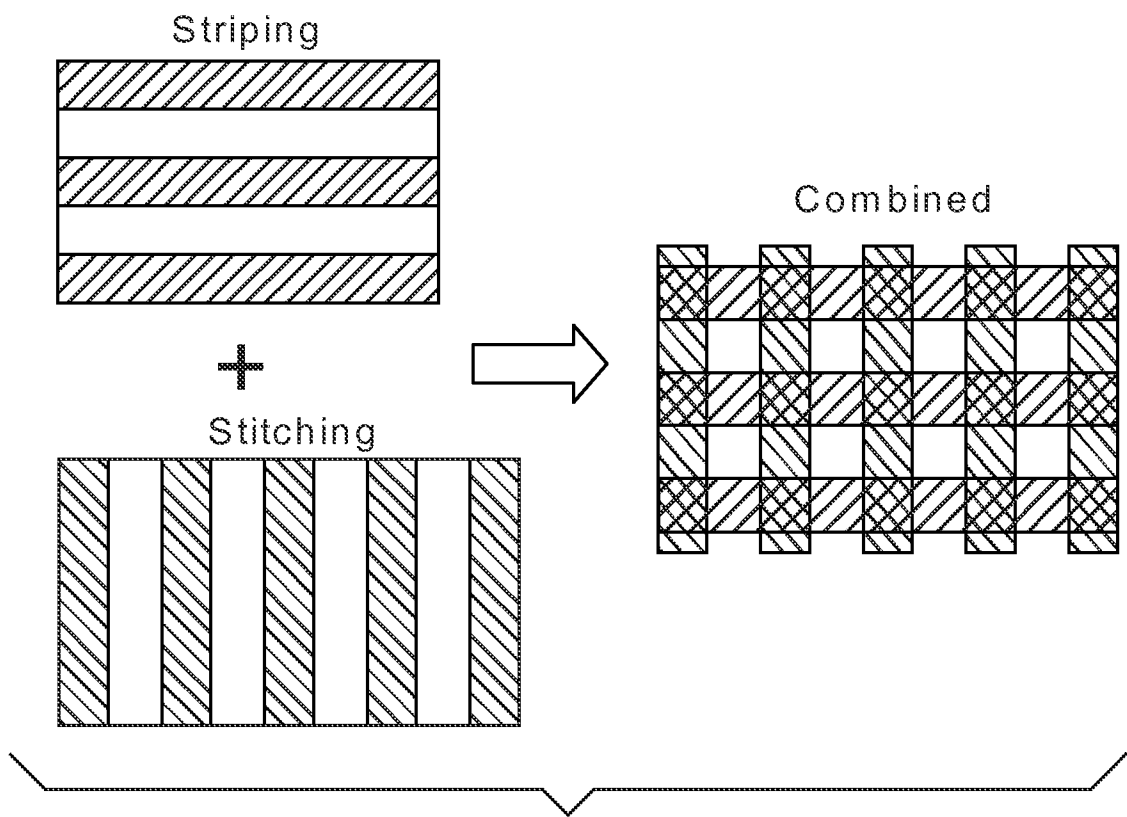
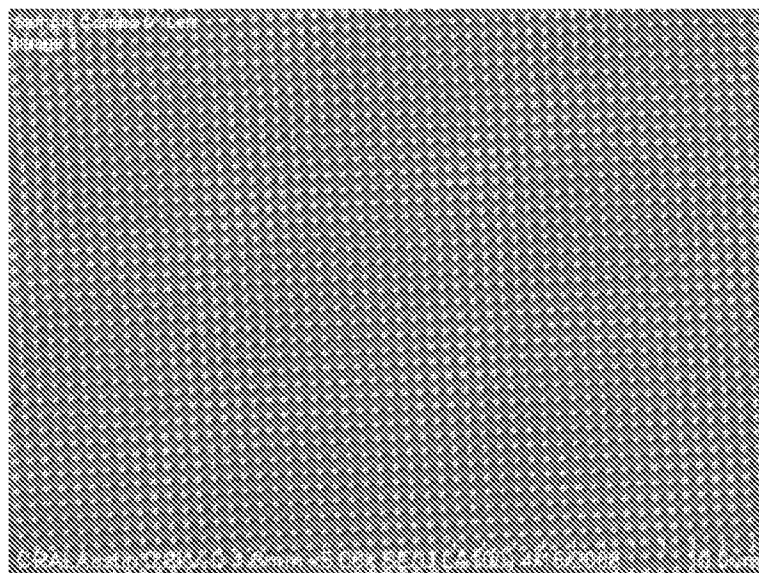
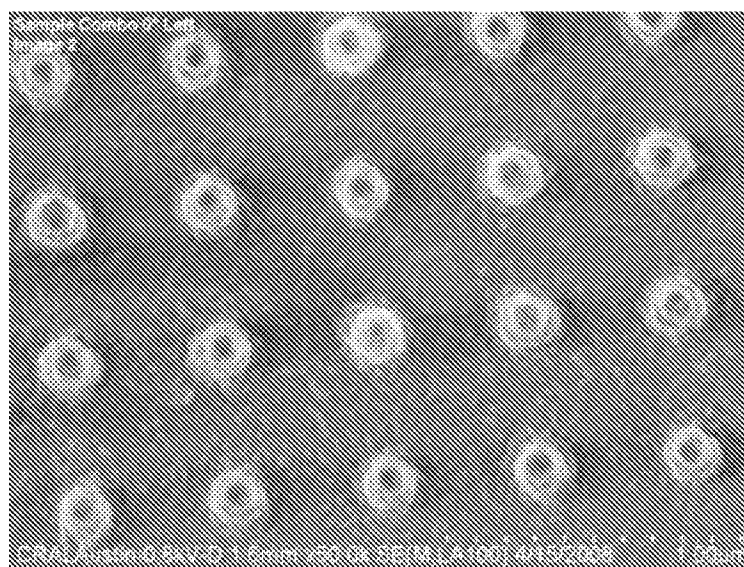


FIG. 3C

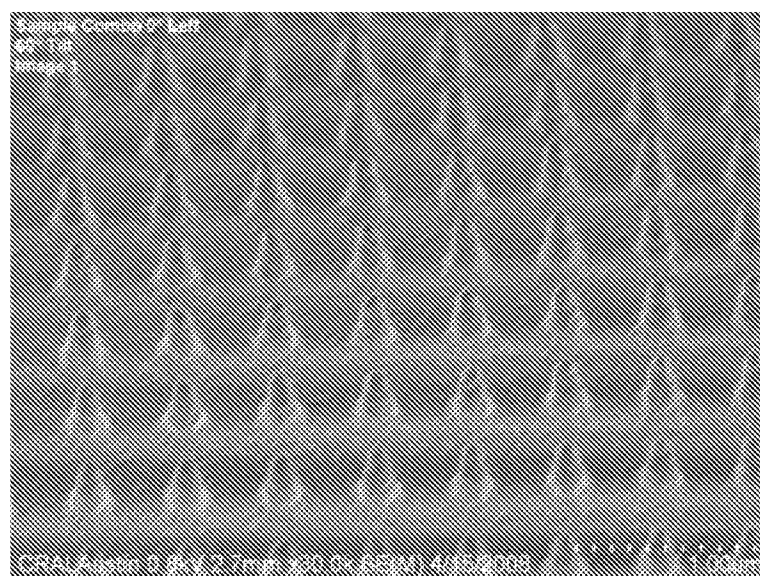
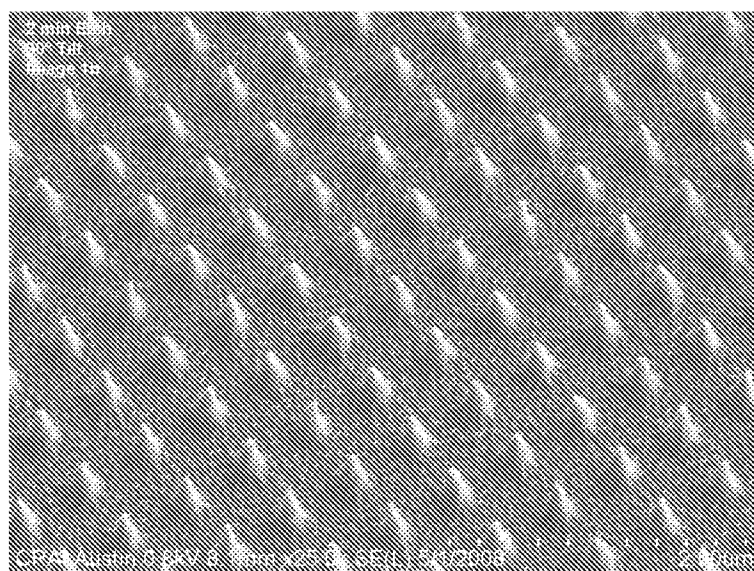
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*FIG. 5A**FIG. 5B*

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*FIG. 5C**FIG. 6*

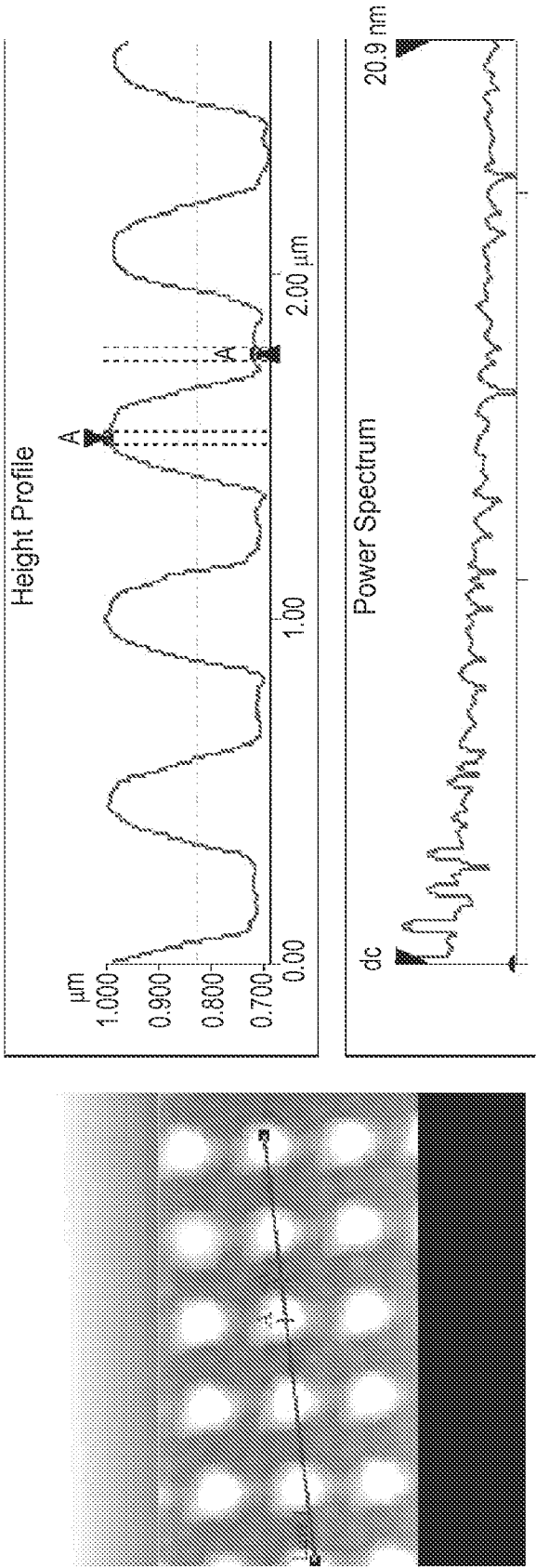


FIG. 7A

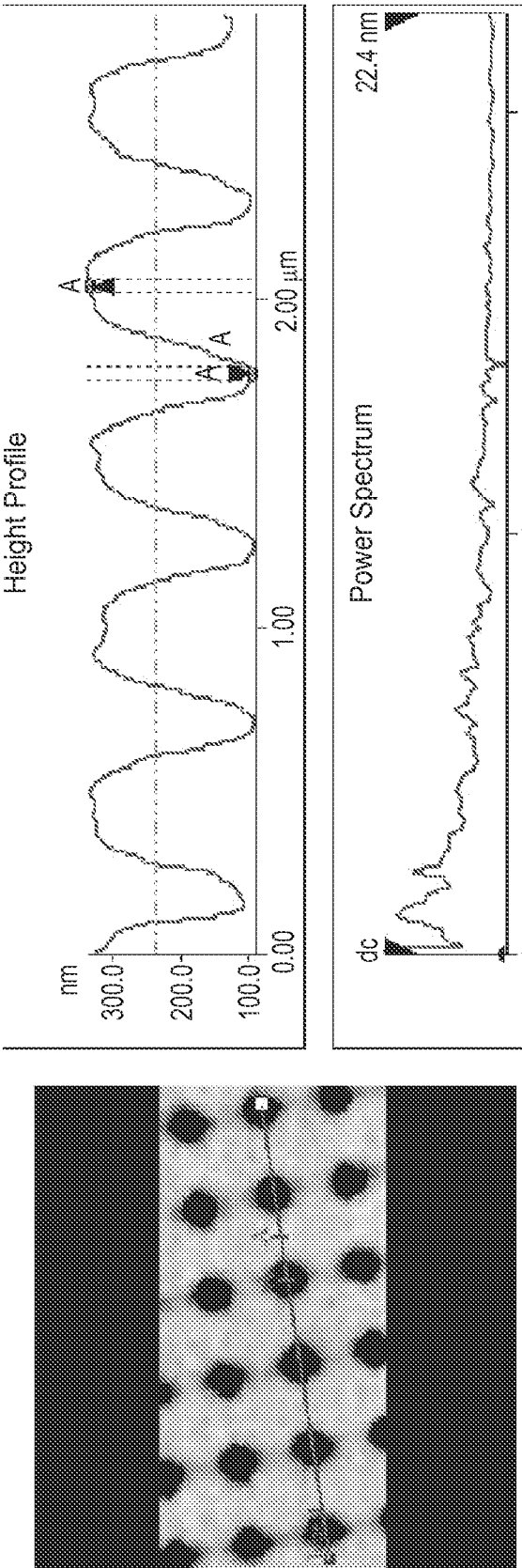


FIG. 7B

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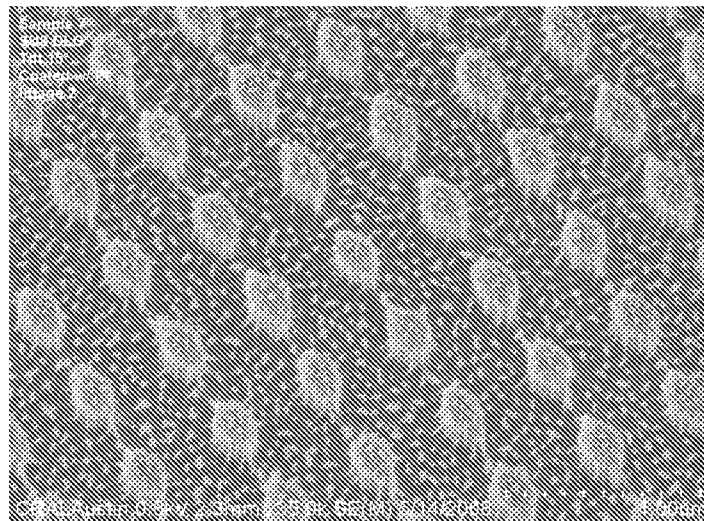


FIG. 8

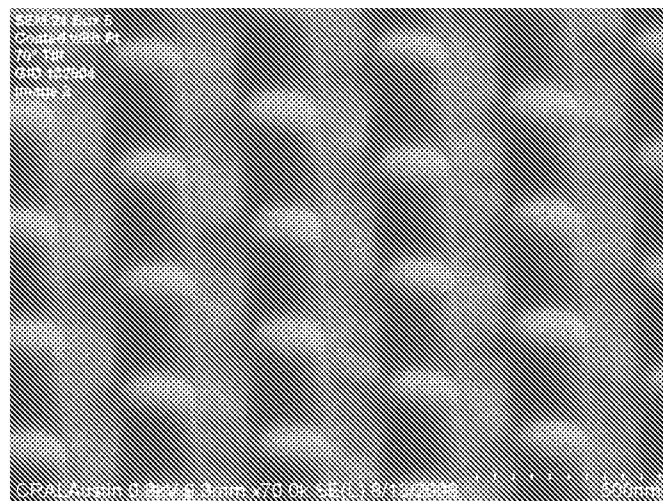


FIG. 9

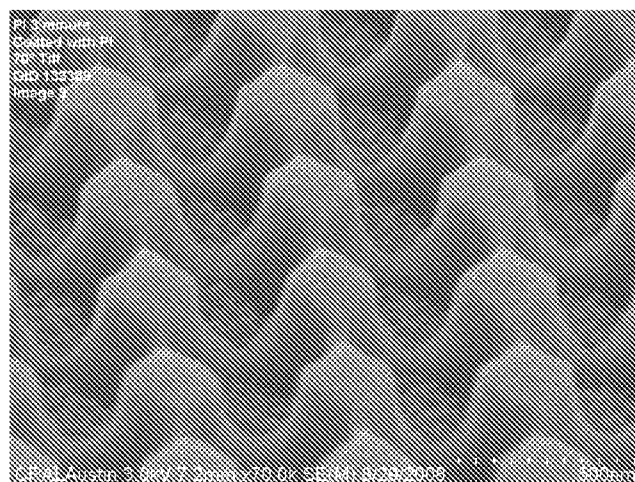


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/067962

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G03F7/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2007/111469 A1 (LG CHEMICAL LTD [KR]; HAN SANG-CHOLL [KR]; OH SEUNG-TAE [KR]; KIM DEOK) 4 October 2007 (2007-10-04)	1-7, 13
Y	paragraph [0012] paragraphs [0026], [0027] paragraph [0032] paragraph [0047]; figure 8 paragraph [0054] paragraph [0025]; figure 3	8-12, 15
X	US 2006/133728 A1 (BIYIKLI LEVENT [US] ET AL) 22 June 2006 (2006-06-22)	14
Y	paragraph [0034]; figure 3 paragraph [0040] paragraph [0030] paragraph [0047] paragraphs [0042], [0043]	8-10, 15
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

3 May 2010

Date of mailing of the international search report

10/05/2010

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Pérennès, Frédéric

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/067962

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008/045011 A1 (FULLER NICHOLAS C [US] ET AL) 21 February 2008 (2008-02-21) claim 4; figure 3 -----	11,12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2009/067962

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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