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(71) Applicant: **AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH** [SG/SG]; 1 Fusionopolis Way, #20-10, Connexis, Singapore 138632 (SG).

(72) Inventors: **KUZNETSOV, Arseniy**; c/o Data Storage Institute, 2 Fusionopolis Way, #08-01, Innovis, Singapore 138634 (SG). **PAN, Zhenying**; c/o Data Storage Institute, 2 Fusionopolis Way, #08-01, Innovis, Singapore 138634 (SG).

(74) Agent: **VIERING, JENTSCHURA & PARTNER LLP**; P.O. Box 1088, Rochor Post Office, Rochor Road, Singapore 911833 (SG).

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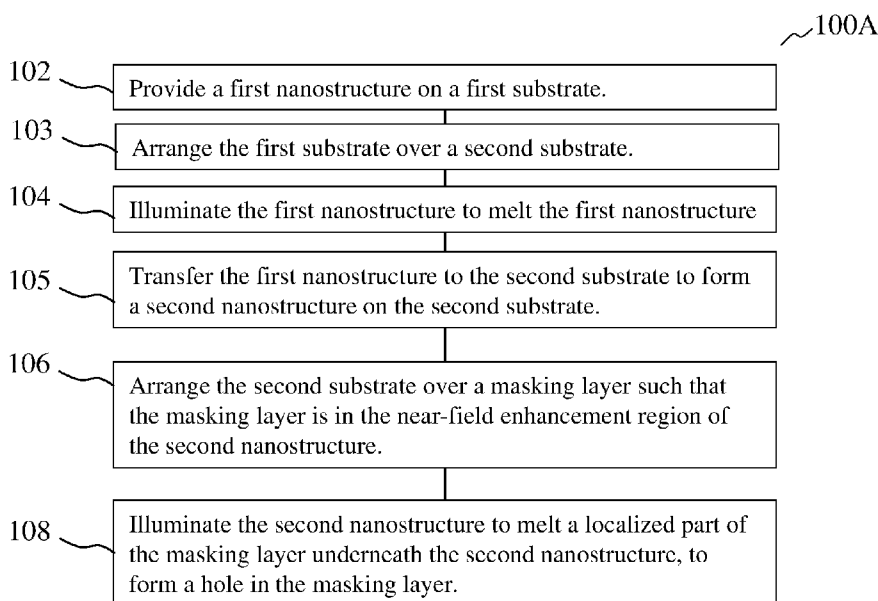


FIG. 1A

(57) Abstract: According to various embodiments, there is provided a photolithography method including providing a first nanostructure on a first substrate; arranging the first substrate over a second substrate; illuminating the first nanostructure to melt the first nanostructure; transferring the first nanostructure to the second substrate to form a second nanostructure on the second substrate; arranging the second substrate over a masking layer such that the masking layer is in the near-field enhancement region of the second nanostructure; and illuminating the second nanostructure to melt a localized part of the masking layer underneath the second nanostructure, to form a hole in the masking layer.



PHOTOLITHOGRAPHY METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of Singapore Patent Application number 10201408009W filed 2 December 2014, the entire contents of which are incorporated herein by reference for all purposes.

TECHNICAL FIELD

[0002] The present invention relates to photolithography methods.

BACKGROUND

[0003] The fast development of nanoscience, especially in the field of nanoelectronics, magnetic recording, nanophotonics and plasmonics, has shown a great demand for new nanostructuring techniques to fulfill many diverse fabrication requirements in terms of resolution, fabrication area, cost efficiency and throughput (wafers/hour). The commonly applied nanolithographic approaches are conventional photolithography and focused particle beams lithography, such as focused electron beams lithography (EBL) or focus ion beams (FIB). As the desired feature size for nanolithography reduces in size, it becomes increasingly difficult, complicated and costly to achieve the desired feature sizes using conventional photolithography. Short optical wavelengths, for example, deep ultraviolet, extreme ultraviolet (EUV), and X-ray regime, may be required to achieve the desired small feature sizes. Although FIB and EBL have been successfully applied in extremely precise nanofabrication, the nature of these techniques may result in low efficiency with long writing times, high costs and poor throughput. The limitations of conventional techniques have motivated the development of alternative approaches such as microcontact printing (soft lithography), nanoimprinting lithography (NIL) and scanning probe lithography. Among these techniques, NIL may offers advantages of producing extremely high resolution nanostructures at large areas (up to wafer scale) with a high throughput and relatively low cost. However, NIL has disadvantages related to its complicated multistep process, overlay alignment, pressure-induced resist redistribution, template wear and lack of high resolution templates whose fabrication rely on other nanolithography techniques.

[0004] Nanostructures, such as nanoparticles also referred as nanopillars or nanoholes, are attractive for a number of potential applications. The potential applications may include production of Spin Transfer Torque Magnetic Random-Access Memory (STT-MRAM) devices, enhancing the efficiency of solar cells, to use for color imaging or to act as plasmonic filters, sensors and lenses. While arrays of the nanoparticles or nanoholes may be fabricated using the aforementioned conventional methods, the conventional methods have drawbacks as discussed above, which limit the size of the nanostructures, the fabrication area, and the throughput that can be fabricated at a reasonable cost. Therefore, there is a need for an alternative method for fabricating the nanostructures.

SUMMARY

[0005] According to various embodiments, there may be provided a photolithography method including providing a first nanostructure on a first substrate; arranging the first substrate over a second substrate; illuminating the first nanostructure to melt the first nanostructure; transferring the first nanostructure to the second substrate to form a second nanostructure on the second substrate; arranging the second substrate over a masking layer such that the second nanostructure is in contact with the masking layer; and illuminating the second nanostructure to melt a localized part of the masking layer underneath the second nanostructure, to form a hole in the masking layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments are described with reference to the following drawings, in which:

[0007] FIG. 1A shows a flow diagram of a photolithography method in accordance to various embodiments.

[0008] FIG. 1B shows a flow diagram of a photolithography method in accordance to various embodiments.

[0009] FIG. 2 shows a flow diagram of a photolithography method in accordance to various embodiments.

[0010] FIGS. 3A-3C shows the three steps of a photolithography method, according to various embodiments.

[0011] FIGS. 4A-4C shows the three steps of a photolithography method, according to various embodiments.

[0012] FIGS. 5A-5C show the change in the feature size of nanostructures during a laser induced transfer according to various embodiments.

[0013] FIG. 6 shows SEM images of nanosphere fabrication.

[0014] FIG. 7 shows SEM images of nanostructures and nanoholes fabricated by a photolithography method according to various embodiments.

[0015] FIG. 8 shows SEM images showing the size of nanoholes fabricated at different irradiation fluencies, in a Cr film arranged underneath gold nanostructures of about 125nm in diameter.

[0016] FIG. 9 shows SEM images showing gold nanodisks fabrication by a photolithography method according to various embodiments.

[0017] FIG. 10 shows a FDTD simulation of an electric-field distribution in the XZ plane for a system including a gold nanostructure, a Cr film and a SiO₂ substrate.

[0018] FIG. 11 shows a FDTD simulation of an electric-field distribution inside the Cr film in the XZ plane, for the system of FIG. 10.

[0019] FIG. 12 shows a FDTD simulation of an electric-field distribution on the Cr film surface in the XY plane, for the system of FIG. 10.

[0020] FIG. 13 shows a FDTD simulation of an electric-field inside the Cr film at a depth of 5nm in the XY plane, for the system of FIG. 10.

[0021] FIG. 14 shows a graph showing the spectral dependence of the optical energy absorbed in the gold nanostructure and the spectral dependence of the optical energy absorbed in three different areas of the Cr film.

[0022] FIG. 15 shows a graph showing the imaginary part of the dielectric constant of gold as a function of wavelength in the spectral range from 400 to 1000 nm.

[0023] FIG. 16 shows a graph showing the imaginary part of the dielectric constant of chromium as a function of wavelength in the spectral range from 400 to 1000 nm.

DESCRIPTION

[0024] Embodiments described below in context of the devices are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments

described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment.

[0025] In the specification the term “comprising” shall be understood to have a broad meaning similar to the term “including” and will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps. This definition also applies to variations on the term “comprising” such as “comprise” and “comprises”.

[0026] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

[0027] Various embodiments are provided for methods, and various embodiments are provided for devices. It will be understood that basic properties of the methods also hold for the devices and vice versa. Therefore, for sake of brevity, duplicate description of such properties may be omitted.

[0028] It will be understood that any property described herein for a specific method may also hold for any method described herein. It will be understood that any property described herein for a specific device may also hold for any device described herein. Furthermore, it will be understood that for any method or device described herein, not necessarily all the components or steps described must be enclosed in the method or device, but only some (but not all) components or steps may be enclosed.

[0029] The fast development of nanoscience, especially in the field of nanoelectronics, magnetic recording, nanophotonics and plasmonics, has shown a great demand for new nanostructuring techniques to fulfill many diverse fabrication requirements in terms of resolution, fabrication area, cost efficiency and throughput (wafers/hour). The commonly applied nanolithographic approaches are conventional photolithography and focused particle beams lithography, such as focused electron beams lithography (EBL) or focus ion beams (FIB). As the desired feature size for nanolithography reduces in size, it becomes increasingly difficult, complicated and costly to achieve the desired feature sizes using conventional photolithography. Short optical wavelengths, for example, deep ultraviolet, extreme ultraviolet (EUV), and X-ray regime, may be required to achieve the desired small feature sizes. Although FIB and EBL have been successfully applied in extremely precise nanofabrication, the nature of these techniques may result in low efficiency with long writing times, high costs and poor throughput. The limitations of conventional techniques have motivated the development of alternative approaches such as microcontact printing (soft

lithography), nanoimprinting lithography (NIL) and scanning probe lithography. Among these techniques, NIL may offers advantages of producing extremely high resolution nanostructures at large areas (up to wafer scale) with a high throughput and relatively low cost. However, NIL has disadvantages related to its complicated multistep process, overlay alignment, pressure-induced resist redistribution, template wear and lack of high resolution templates whose fabrication rely on other nanolithography techniques.

[0030] Nanostructures, such as nanoparticles also referred as nanopillars or nanoholes, are attractive for a number of potential applications. The potential applications may include production of Spin Transfer Torque Magnetic Random-Access Memory (STT-MRAM) devices, enhancing the efficiency of solar cells, to use for color imaging or to act as plasmonic filters, sensors and lenses. While arrays of the nanoparticles or nanoholes may be fabricated using the aforementioned conventional methods, the conventional methods have drawbacks as discussed above, which limit the size of the nanostructures, the fabrication area, and the throughput that can be fabricated at a reasonable cost. Therefore, there is a need for an alternative method for fabricating the nanostructures.

[0031] In the context of various embodiments, “nanoparticles” may be but is not limited to being interchangeably referred to as “nanopillars”.

[0032] In the context of various embodiments, “first substrate” may be but is not limited to being interchangeably referred to as “template structure”, “initial template” or “pre-defined template”.

[0033] In the context of various embodiments, “second substrate” may be but is not limited to being interchangeably referred to as “flexible substrate”.

[0034] In the context of various embodiments, “recording mask” may be but is not limited to being interchangeably referred to as “masking layer” or “recording layer”.

[0035] In the context of various embodiments, “third substrate” may be but is not limited to being interchangeably referred to as “substrate of interest”.

[0036] In the context of various embodiments, “near-field enhancement region” may be but is not limited to being interchangeably referred to as “optical enhancement region” or “optical near-field enhancement region”.

[0037] In the context of various embodiments, “etching mask material” may be but is not limited to being interchangeably referred to as “masking material”.

[0038] FIG. 1A shows a flow diagram 100A showing a photolithography method according to various embodiments. The photolithography method may include a plurality of processes 102, 103, 104, 105, 106 and 108. In 102, a first nanostructure may be provided on a first

substrate. In 103, the first substrate may be arranged over a second substrate. In 104, the first nanostructure may be illuminated to melt the first nanostructure. In 105, the first nanostructure may be transferred to the second substrate to form a second nanostructure on the second substrate. In 106, the second substrate may be arranged over a masking layer such that the masking layer is in the near-field enhancement region of the second nanostructure. In 108, the second nanostructure may be illuminated to melt a localized part of the masking layer underneath the second nanostructure, to form a hole in the masking layer. The masking layer may include metal, such as chromium.

[0039] In other words, according to various embodiments, the photolithography method may include in 102, providing a first nanostructure on a first substrate; in 103, arranging the first substrate over a second substrate; in 104, illuminating the first nanostructure to melt the first nanostructure; in 105, transferring the first nanostructure to the second substrate to form a second nanostructure on the second substrate by a transfer process; in 106, arranging the second substrate with the second nanostructure over a masking layer such that the masking layer is in the near-field enhancement region of the second nanostructure. The masking layer may be in contact with the second nanostructure; and in 108, illuminating the second nanostructure. In 102, the first nanostructure may be positioned on top of the first substrate. The first substrate may be arranged over the second substrate such that the first nanostructure may be in close proximity to the second substrate, for example at a distance at least substantially in the range of less than one micron or at a distance comparable to the size of the first nanostructure. The first nanostructure may also be in contact with the second substrate. The first nanostructure may include plasmonic metals, such as at least one of gold, silver, aluminum or copper. The first nanostructure may be at least substantially shaped as one of a prism or a disk. The first substrate may be at least substantially transparent and may include at least one of glass or quartz. The first nanostructure may be provided on the first substrate using any one of photolithography, e-beam lithography, nano-imprint lithography or nanosphere lithography. In 104, the first nanostructure may be melted by the illumination. The illumination may be a visible light. The visible light may be generated by a laser. The melted first nanostructure is also referred herein as a second nanostructure. The second nanostructure may be transferred by the illumination process onto the second substrate placed in contact or close to the first substrate. The second nanostructure may be at least substantially spherical and may be partially embedded onto the second substrate. The second substrate may include an at least substantially flexible material. The second substrate may include a polymer, such as polydimethylsiloxane (PDMS). In 108, a localized part of the

masking layer at least substantially directly underneath the second nanostructure may be melted as a result of illuminating the second nanostructure. The illumination of the second nanostructure may include providing a visible light. The visible light may be generated by a laser. The second nanostructure may enhance an optical field in a near-field region of the second nanostructure when the second nanostructure is illuminated. The enhanced optical field may melt a localized part of the masking layer placed in the region of optical near-field enhancement region. The enhanced optical field may melt a localized part of the masking layer placed in contact with or close to the second nanostructure. The melting of the localized part of the masking layer may form a hole in the masking layer. The hole may be smaller than the second nanostructure and the second nanostructure may be smaller than the first nanostructure. The photolithography method may include having a plurality of first nanostructures arranged on the first substrate; illuminating the plurality of first nanostructures to form a plurality of second nanostructures on the second substrate by transfer process; and illuminating the plurality of second nanostructures to form a plurality of holes in the masking layer. The pattern of the plurality of first nanostructures may be replicated on the masking layer as a pattern of the plurality of holes.

[0040] FIG. 1B shows a flow diagram 100B showing a photolithography method according to various embodiments. The photolithography method may be used to fabricate a nanohole. The photolithography method of FIG. 1B may be similar to the photolithography method of FIG. 1A in that it may include 102, 103, 104, 105, 106 and 108. In addition to the photolithography method of FIG. 1A, the photolithography method of FIG. 1B may further include 110, in which a third substrate provided under the masking layer may be etched, to extend the hole into the third substrate. The photolithography method may further include 112, in which the masking layer is removed. In other words, the masking layer formed in 108 may be used as an etching mask over the third substrate for etching the third substrate, so as to form a hole in the third substrate. The masking layer may then be removed after the third substrate is etched. The hole formed in the third substrate may be a nanohole that is smaller in size than each of the first nanostructure and the second nanostructure.

[0041] FIG. 2 shows a flow diagram 200 showing a photolithography method according to various embodiments. The photolithography method may be used to fabricate a nanopillar. The photolithography method of FIG. 2 may be similar to the photolithography method of FIG. 1A in that it may include 102, 103, 104, 105, 106 and 108. In addition to the photolithography method of FIG. 1A, the photolithography method of FIG. 2 may further include processes 214, 216, 218, 220, 222 and 224. In 214, an interstitial layer may be

provided over a third substrate, wherein the interstitial layer and the third substrate may be provided under the masking layer. In 216, a protective layer may be provided between the interstitial layer and the masking layer. In 218, the interstitial layer may be etched to extend the hole through the interstitial layer to reach the third substrate. In 220, a material of interest may be deposited onto the third substrate through the extended hole. The material of interest may include an etching mask material. In 222, the interstitial layer may be removed and the masking layer with protective layer may be removed. In 224, the third substrate may be etched to form a pillar, a position of the pillar corresponding to a position of the hole. In other words, an interstitial layer may be provided between the third substrate and the masking layer. A protective layer for protecting the interstitial layer may optionally be arranged between the interstitial layer and the masking layer. The protective layer may include silicon dioxide. The interstitial layer may be etched using the masking layer as an etching mask, so as to form a hole in the interstitial layer wherein the hole in the interstitial layer corresponds to the position of the hole in the masking layer. The hole in the interstitial layer may extend through the entire depth of the interstitial layer such that the hole ends at a top surface of the third substrate that is in contact with the interstitial layer. A material of interest may be deposited. The material of interest may be deposited over the interstitial layer. If there is a protective layer, the material of interest may be deposited over the protective layer. The material of interest may be deposited into the hole of the interstitial layer such that the material of interest is deposited on the top surface of the third substrate at a position corresponding to the hole of the interstitial layer. The material of interest may include a masking material. The hole in the interstitial layer can be said to be functioning as a conduit for guiding the deposition of the masking material at the desired position on the third substrate. After the masking material has been deposited, the interstitial layer and the masking layer may be removed. The masking material deposited over the interstitial layer or the protective layer may also be removed, revealing the third substrate and nanostructures out of the masking material deposited on the third substrate through the holes in the interstitial layer. If a protective layer is arranged between the interstitial layer and the masking layer, the protective layer may also be removed. The third substrate may then be etched, with the deposited nanostructures of masking material serving as an etching mask. The etching may result in a pillar formed on the third substrate, the pillar being a portion of the third substrate that is not etched away as it lies beneath the deposited masking material. The pillar formed on the third substrate may be a nanopillar. The nanopillar may have a diameter that is smaller

than each of the diameter of the first nanostructure and the diameter of the second nanostructure. The masking material on top of the nanopillar may be removed.

[0042] A photolithography method according to various embodiments is a new lithography technique that may be able to record controllable patterns in large scale of up to wafer size, using plasmonic nanostructures. The method may achieve rapid large-scale laser-based fabrication of nanoparticles and nanoholes arrays with controlled design and position. The method may include photolithography processes, including utilizing the plasmonic nanostructures as near-field light energy concentrators to record nanoholes into a recording material or an etch mask material. The etch mask material may be used to fabricate holes or pillars out of a desired material. The feature sizes achievable through the method may be at least equal to or smaller than 40nm or even smaller than 20nm. The small feature sizes may be achievable even on curved or rough surfaces. The plasmonic nanostructures may be reused for multiple times to produce multiple replications of nanoparticles or nanohole arrays. Moreover, the feature size may be decreased during the replication processes, at up to a few times per replication process. As such, the method may provide the possibility to further reduce the feature size to below the aforementioned limits. The method may only require visible light sources instead of costly short optical wavelengths. The method may also do away with dry resist processes.

[0043] A photolithography method according to various embodiments may be a laser-based method. The method may be able to produce ordered sub-wavelength arrays of at least one of nanoholes or nanoparticles. The method may be able to produce arrays with feature size ranging from a few tens of nanometers to a few hundreds of nanometers. The feature size may be controllably varied. The method may satisfy the requirements of high resolution and large fabrication area with a fast processing speed. The method, also referred herein as plasmonic nanoparticle lithography, may include laser induced transfer (LIT) and light-induced near-field nanomodification. The light-induced near-field nanomodification may make use of the optical enhancement and thermal effect in the near-field of plasmonic nanostructures, to create holes in a masking layer underneath the plasmonic nanostructures. The plasmonic nanostructures may be at least substantially spherical in shape. The method may produce ordered a sub-wavelength nanohole array in a thin mask layer upon laser or incoherent light exposure on the plasmonic nanostructures. The thin mask layer may be a metallic film, such as a chromium film. The mask layer with the nanohole array may be arranged on a desired substrate for etching a nanohole array in the desired substrate, or used to create an array of nanopillars on the desired substrate through post-processing.

[0044] A photolithography method according to various embodiments may be a laser-based nanofabrication method including a combination of laser induced transfer (LIT) and laser- or incoherent light-induced near-field nanomodification. The method may provide for fast fabrication of centimeter-scale or wafer-scale controllable structures and arrays of nanoholes or nanoparticles with sizes ranging from a few tens to a few hundreds nanometers. The method may include fabricating large-scale spherical or spheroidal metal nanostructures on a flexible substrate, using pre-defined templates using the LIT technique. The flexible substrate may include a polymer such as polydimethylsiloxane (PDMS). The method may further include applying the nanostructures as a near-field mask for light-induced recording of an array of nanoholes in a thin metallic film or membrane using the near-field light energy concentrated under the nanostructures. The method may further include applying the thin metallic film containing the array of nanoholes, as an etching mask to form an array of nanoholes in the desired material. The thin metallic film can also be used as an etching mask in a process to create an array of nanopillars in the desired material. An advantage of the method is its ability to scale the size of the fabricated holes or nanoparticles down to a few nanometers or several tens of nanometers. This may be achievable due to a possibility for efficient feature size reduction at each step of the process. The process may also be realized without any size reduction, to fully reproduce the initial template pattern. The laser or light processes required in the method may be realized under large defocused light beams with sufficient light intensity and under high translation speed, which makes this method suitable for large-scale (wafer or more) high-throughput fabrication of nanopillars or nanoholes.

[0045] FIG. 3A includes a diagram showing a first step 300A of a photolithography method, according to various embodiments. The method may be used to fabricating an array of nanoholes. The method may include three process steps. The first step 300A, also referred herein as step 1, may include fabricating at least one second nanostructure 336 or an array of second nanostructures 336 on top of a flexible substrate 334 using laser induced transfer (LIT). The second nanostructure 336 may be metal nanoparticles. The second nanostructure 336 may be the second nanostructure referred to in FIG. 1A, FIG. 1B and FIG. 2 while the flexible substrate 334 may be the second substrate referred to in FIG. 1A, FIG. 1B and FIG. 2.

[0046] The first step 300A may start with illuminating an initial template. The initial template may include a first substrate 330 and at least one pre-defined structure 332 or an array of pre-defined structures 332 formed on the first substrate 330. The first substrate 330 may be at least substantially transparent or optically transmissive and may include at least

one of glass or quartz. The second substrate 334 may be a polymeric film, for example, PDMS. The pre-defined structure 332 may be the first nanostructure referred in FIG. 1A, FIG. 1B and FIG. 2. The pre-defined structure 332 may be a plasmonic nanostructure and may include at least one of gold, silver, aluminum or copper. The pre-defined structure 332 may be fabricated on the first substrate 330 by existing lithographic technique such as but not limited to photo-lithography, e-beam lithography, nano-imprint lithography or nanosphere lithography. The shape of the pre-defined structure 332 may depend on the nanofabrication technique. For example, the pre-defined structure 332 may be a triangular prism if it is fabricated using nanosphere lithography, or it may be a disk or a prism if it is fabricated using any one of e-beam, photo- and nanoimprint lithography. The first substrate 330 may be arranged over the second substrate 334 such that the pre-defined structure 332 on the first substrate 330 may be brought into contact with the second substrate 334. The pre-defined structure 332 may then be irradiated by at least one of laser or intense light through the at least substantially transparent first substrate 330. The pre-defined structure 332 may melt under the irradiation and transform into an at least substantially spherical droplet by surface tension forces of the molten pre-defined structure 332. During the transformation, the molten pre-defined structure 332 may be transferred away from the first substrate 330 onto the second substrate 334. The transferred molten pre-defined structure 332 may solidify to form the second nanostructure 336. The second nanostructure 336 may be at least substantially spherical in shape or at least substantially spheroidal in shape, due to the surface tension forces during its molten state. The spatial arrangement of the second nanostructures 336 on the second substrate 334 may be at least substantially similar to the spatial arrangement of the pre-defined structures 332 on the first substrate 330. In other words, the spatial arrangement as defined by the initial template may be conserved on the second substrate 334. The size of the fabricated second nanostructures 336 and the distance between them may be defined by the size and distances between the lithographically fabricated pre-defined structures 332 on the surface of the first substrate 330. The second nanostructures 336 may modify the surface of the flexible material 334, due to the high temperature of the second nanostructures 336 when they are in the molten state. After the second nanostructures 336 solidify, the second nanostructures 336 may be at least partially embedded into the second substrate 334, which make the second nanostructures 336 more rigid to external treatments.

[0047] FIG. 3B includes a diagram showing a second step 300B of the photolithography method. The second step 300B, also referred herein as step 2, may include fabricating nanoholes 340 in a recording mask 338 by light illumination, using the second substrate 334

with second nanostructures 336 from the first step. The recording mask 338 may be the masking layer as referred to in FIG. 1A, FIG. 1B and FIG. 2 while the nanohole 340 may be the hole in the masking layer as referred to in FIG. 1A, FIG. 1B and FIG. 2. The second substrate 334 with the second nanostructures 336 formed in the first step may be arranged over the recording mask 338, to bring the second nanostructures 336 into contact with the recording mask 338. The recording mask 338 may be deposited on top of a substrate of interest 342. The recording mask may be a thin metallic film, such as a chromium film. The substrate of interest 342 may be the third substrate referred to in FIG. 1A, FIG. 1B and FIG. 2. The illumination of the light on the second substrate 334 may cause nanoholes 340 to be formed in the recording mask 338. The pattern of the nanoholes 340 may correspond to the pattern of the second nanostructures 336 on the second substrate 334. In other words, the recording mask 338 may be used to record the array pattern of the second nanostructures 336. The illumination for conducting the pattern transfer process may use one of laser or intense incoherent light.

[0048] FIG. 3B further includes a schematic diagram 302 showing the nanoholes 340 formed in the recording mask 338. The second nanostructures 336 may serve as optical near-field energy concentrators, which may enhance the optical field in the near-field region around the second nanostructures 336 and promote the local melting and removal of the recording mask 338 just beneath the second nanostructures 336. As a result, a hole may be created in the recording mask 338 beneath each second nanostructure 336.

[0049] FIG. 3C includes a diagram showing a third step 300C of the photolithography method. The third step 300C, also referred herein as step 3, may include a post-processing step to transfer the fabricated pattern into the substrate of interest 342. The post-processing step may include etching the recording mask 338, and may further include removing the recording mask 338 after the nanohole pattern is transferred to the substrate of interest 342. In other words, the recording mask 338 may be used as a removable etching hard mask. The pattern on the recording mask 338 may be transferred into the substrate of interest 342 by etching, before removal of the recording mask 338 by an etchant. The post-processing step may result in an array of holes formed in the substrate of interest 342.

[0050] FIG. 4A includes a diagram showing a first step 400A of a photolithography method, according to various embodiments. The photolithography method may be used to fabricate an array of nanopillars. The photolithography method may include three process steps. The first step 400A, also referred herein as step 1, may be at least substantially identical or similar to the first step 300A of FIG. 3A. The first step 400A may include fabricating second

nanostructures 336 on top of a second substrate 334 using laser induced transfer (LIT). The second nanostructures 336 may be on top of the second substrate 334 or partially embedded in the second substrate 334. The second nanostructure 336 may be the second nanostructure referred to in FIG. 1A, FIG. 1B and FIG. 2 while the flexible substrate 334 may be the second substrate referred to in FIG. 1A, FIG. 1B and FIG. 2. The flexible substrate 334 may be a polymeric film, for example, PDMS. The flexible substrate 334 may be at least substantially transparent or optically transmissive. The first step may start with an initial template including at least one pre-defined structure 332 formed on a first substrate 330. The pre-defined structure 332 may be the first nanostructure referred in FIG. 1A, FIG. 1B and FIG. 2. The pre-defined structure 332 may be a plasmonic nanostructure. The template substrate 330 may have an array of pre-defined structures 332 formed thereon. The first substrate may be a transparent substrate. The pre-defined structure 332 may be formed on the template substrate 330 by existing lithographic technique such as but not limited to photo-lithography, e-beam lithography, nano-imprint lithography or nanosphere lithography. The pre-defined structure 332 may include at least one of gold, silver, aluminum or copper. The first substrate 330 may include at least one of glass or quartz. The shape of the pre-defined structure 332 may depend on the nanofabrication technique. The pre-defined structure 332 may be a nanoparticle having the shape of a triangular prism if it is fabricated using nanosphere lithography, or the shape of a disk or a prism if it is fabricated using any one of e-beam, photo- and nanoimprint lithography.

[0051] FIG. 4B includes a diagram showing a second step 400B of the photolithography method. The second step 400B, also referred herein as step 2, may include recording the pattern of the second nanostructure 336 on a recording mask 338 using light illumination. The recording mask 338 may be the masking layer as referred to in FIG. 1A, FIG. 1B and FIG. 2. The recording mask 338 may be a metallic film, for example a chromium film. The recording mask 338 may be arranged over an interstitial layer 442. Optionally, the recording mask 338 may be arranged over a protective layer 440 covering the interstitial layer 442. The protective layer 440 may be sandwiched between the recording mask 338 and the interstitial layer 442. The interstitial layer 442 may be the interstitial layer referred to in FIG. 2. The interstitial layer 442 may be a removable layer including a photoresist material. The protective layer 440 may be optionally arranged over the interstitial layer 442 to prevent modification of the photoresist material. The protective layer 440 may include silica. The interstitial layer 442 may be arranged over a substrate of interest 342. The substrate of interest 342 may be the third substrate referred to in FIG. 1A, FIG. 1B and FIG. 2. The

flexible substrate 334 with at least one second nanostructure 336, as formed in the first step 400A of FIG. 4A, may be arranged over the recording mask 338. Light may be illuminated on the flexible substrate 334, causing at least one nanohole 340 to be formed in the recording mask 338. The nanohole 340 may be the hole in the masking layer as referred to in FIG. 1A, FIG. 1B and FIG. 2.

[0052] FIG. 4B further includes a schematic diagram 402 showing the nanoholes 340 formed in the recording mask 338. The second step 400B of the method may include bringing the second nanostructures 336 on the flexible substrate 334 into contact with the recording mask 338. As the light is illuminated on the flexible substrate 334, the second nanostructures 336 may act as optical near-field energy concentrators to enhance the optical field in the near-field region around the second nanostructures 336. The enhanced optical field in the near-field region around the second nanostructures 336 may cause localized melting in the recording mask 338. The melting may occur at positions on the recording mask 338 that are directly underneath the second nanostructures 336. The localized melting may result in nanoholes 340 formed in the recording mask 338, such that the recording mask 338 has nanoholes 340 formed therein, directly under each second nanostructure 336.

[0053] FIG. 4C includes a series of diagrams 404, 406, 408, 410 and 412, showing a third step 400C of the photolithography method. The third step 400C, also referred herein as step 3, may include transferring the pattern on the recording mask 338 to the interstitial layer 442 by etching, thereby forming extended nanoholes 450 in the interstitial layer 442. The extended nanohole 450 may be the extended hole referred to in FIG. 2. The third step 400C may further include depositing an etch mask 444 into the extended nanoholes 450 to form a nanoparticle 446 inside each extended nanohole 450. The etch mask 444 may be the material of interest referred to in FIG. 2. The third step 400C may further include removal of the interstitial layer 442 and may further include removal of the protective layer 440 and the etch mask 444, leaving behind the substrate of interest 342 with an array of nanoparticles 446. The substrate of interest 342 may be etched to form an array of nanopillars 448, using the array of nanoparticles 446 as an etch mask. The nanopillar 448 may be the pillar referred to in FIG. 2.

[0054] Diagram 404 shows an initial state before the pattern of nanoholes 340 on the recording mask 338 is transferred to the interstitial layer 442. Diagram 406 shows nanoholes 340 in the recording mask 338 being deepened by etching, to extend into the interstitial layer 442 and the protective layer 440, if present. The etching may be performed through the nanoholes 340, to etch both the residual recording mask 338 and the entire depth of the interstitial layer 442, to reach the substrate of interest 342. The deepened nanoholes are also

referred herein as extended nanoholes 450. Diagram 408 shows depositions of the etch mask 444 onto the substrate of interest 342 through the extended nanoholes 450, thereby forming nanoparticles 446 in the extended nanoholes 450. The etch mask 444 may include a hard etch mask material, for example chromium or gold. Diagram 410 shows the nanoparticles 446 on the substrate of interest 342, after the recording mask 338, the interstitial layer 442 and the protective layer 440 are lift off. As a result, the substrate of interest 342 may be covered by an array of nanoparticles 446. The nanoparticles 446 may be used to create an array of nanopillars 448 on the substrate of interest 342. Diagram 412 shows nanopillars 448 formed on the substrate of interest 342, after the substrate of interest 342 is further etched. The remaining nanoparticles 446 can further be washed or etched away by wet etching process to leave an array of nanopillars 448 on the substrate of interest. The size of the nanoparticle 446 may be adjusted to be similar in size as the pre-defined structure 332 or may also be adjusted to be several times smaller than the pre-defined structure 332, depending on the process parameters. If the nanoparticle 446 is made of the same plasmonic material as the pre-defined structure 332, the nanoparticle 446 may be reused after the lift off process (diagram 410) for the same replication process at least one more time. In other words, the nanoparticle 446 may be used to replace the pre-defined structure 332 in the first step 400A of FIG. 4A or the first step 300A of FIG. 3A. Iterations of the three processes steps 1 to 3 may lead to significant reductions in the size of the nanoparticle 446, of up to three times of the feature size while maintaining the spatial arrangement of the pre-defined structures. Therefore, this method may be used to reduce the feature size down to very small levels, which are not achievable by existing lithographic techniques.

[0055] FIGS. 5A-5C show the change in the feature size of nanostructures during the process of laser induced transfer (LIT) according to various embodiments.

[0056] FIG. 5A shows a scanning electron microscope (SEM) image 500A of a gold nanodisk array on quartz fabricated by E-beam lithography. The gold nanodisk may have a diameter of about 120 nm and a thickness of about 20 nm. The array of gold nanodisks may be the pre-defined structures 332 of FIG. 3A or FIG. 4A. The quartz may be the first substrate 330 on which the pre-defined structures 332 are formed on. The gold nanodisk array on quartz may be the initial template structure described in relation to FIGS. 3A and 4A.

[0057] FIG. 5B shows a SEM image 500B showing the gold nanodisk on quartz of FIG. 5A transformed into spheres with diameters of about 85 nm by laser melting with a 40-fs laser working at 1KHz and a fluence of about 0.6 J/cm². The SEM image 500B shows an intermediate stage when the nanodisks have been already transformed into spheres but not yet

transferred to a second substrate. The irradiation fluence is at slightly below the transfer threshold. The spheres may be the molten pre-defined structures 332 described in relation to FIGS. 3A and 4A.

[0058] FIG. 5C shows a SEM image 500C showing nanospheres transferred onto a PDMS substrate with a 40-fs laser working at 1KHz with a fluence of $\sim 0.9 \text{ J/cm}^2$. The PDMS substrate may be the second substrate 336 of FIGS. 3A and 4A. The nanospheres may be the second nanostructures 336 of FIGS. 3A-3B and 4A-4B. The laser transfer may be realized in scanning mode at a translation speed of about 0.1 mm/sec. The laser beam may have a flat-top square-shaped profile with the size of $6 \times 6 \text{ } \mu\text{m}^2$. The diameter of the nanosphere is about 80nm. As can be seen from FIGS. 5A-5C, during the LIT process, in other words, step 1 of the photolithography method, the particle size may be reduced by the transformation from a flat disk shape into a sphere due to the conservation of volume. The LIT process may be conducted by focused laser beams, as well as by bright intense light flashes. As such, it may be possible to use the LIT process for both precise positioning of the nanospheres as well as for large-scale nanosphere array fabrication. The size of the nanosphere array may be limited only by the initial template.

[0059] FIG. 6 shows a first SEM image 600A and a second SEM image 600B, both showing nanosphere fabrication at a larger scale than that of FIGS. 5A-C. The first SEM image 600A shows an array of nanospheres transferred onto a PDMS layer. The nanospheres may have diameters of about 80nm each. The second SEM image 600B is a magnification of the first SEM image 600A.

[0060] FIG. 7 includes SEM images 700A, 700B and 700C showing nanostructures and nanoholes fabricated by the photolithography method according to various embodiments. FIG. 7 further includes magnified images 702A, 702B and 700C, which are the magnified views of 700A, 700B and 700C respectively. The SEM image 700A shows an array of nanospheres on a PDMS layer where the diameter of each nanosphere is about 80 nm. In other words, with reference to FIGS. 3A and 4A, the SEM image 700A shows the second substrate 334 with second nanostructures 336 partially embedded therein. The SEM image 700B shows an array of nanoholes in a 20nm thick Cr film which is used as a recording mask on top of a glass substrate. In other words, with reference to FIGS. 3B and 4B, the SEM image 700B shows the recording mask 338 on top of the substrate 342 having nanoholes 340 formed therein, directly replicating the pattern of the nanospheres on the PDMS. The diameters of the nanoholes in the Cr film are about 40nm each. The recording was realized by single pulses of 40-fs laser at a fluence of about 0.22 J/cm^2 . The size of the fabricated holes is

about half the size of the nanospheres of 700A. The SEM image 700C shows an array of nanoholes in a glass substrate, after etching of the glass substrate through the holes in chromium recording mask and complete removal of the chromium recording mask and deposition of a thin platinum layer to facilitate the SEM imaging. The array of nanoholes was transferred into the glass substrate by etching through the Cr film mask fabricated at the previous step. In other words, with reference to FIG. 3C, the SEM image 700C shows the nanohole array formed in the substrate of interest 342 by etching the substrate of interest 342 using the Cr film as an etch mask. The pattern of holes fabricated during the second step is simply transferred into the underlying substrate of interest by etching. The Cr film acting as an etching mask is subsequently removed. It can be seen that the size of the hole in the SEM image 700C is similar to the size of holes obtained in the chromium film during the previous step, as shown in the SEM image 700B. The hole diameter is about 50nm. The reduction in feature size from the nanosphere of the SEM image 700A, to the nanohole of the SEM image 700B, may be explained by the focusing of optical energy under the nanosphere close to contact with the Cr film. Therefore, the proposed method allows a significant reduction of the feature size and going beyond the sizes allowed by standard lithographic techniques, which can be used for the initial template fabrication.

[0061] FIG. 8 includes SEM images 800A, 800B and 800C which show the size of nanoholes fabricated at different irradiation fluencies, in a Cr film arranged underneath gold nanostructures of about 125nm in diameter. The SEM image 800A shows a nanohole fabricated at laser fluence of 0.12 J/cm^2 , the SEM image 800B shows a nanohole fabricated at laser fluence of 0.26 J/cm^2 and the SEM image 800C shows a nanohole fabricated at laser fluence of 0.44 J/cm^2 . As can be seen from the SEM images 800A-800C, the depth and lateral size of the fabricated holes may depend on the irradiation fluence. Therefore, the irradiation fluence can be adjusted to achieve the required nanohole parameters. For irradiation fluences close to the melting threshold, the holes are not formed through the entire thickness of the Cr film. However, even in this case the pattern can be transferred into the substrate of interest by subsequent post processing, for example by etching. If the fluence of light irradiation is chosen close enough to the nanohole creation threshold, the spherical nanostructures in the flexible substrate may not be affected by the recording process and may be reused as a recording mask for more than one time.

[0062] FIG. 9 includes SEM images 900A, 900B and 900C showing gold nanodisks fabrication by a photolithography method according to various embodiments. The SEM image 900A shows a nanosphere array on a PDMS film. The diameter of the nanosphere may

be about 80 nm. The array may be similar to the array shown in FIG. 6. The SEM image 900B shows an array of nanoholes fabricated in a Cr film on top of SiO₂/photoresist layer on top of the glass substrate, by a single pulse of a 40-fs laser with a laser fluence of 0.54 J/cm². The SEM image 900C shows a gold nanodisk array fabricated on the glass substrate through the post processing steps shown in FIG. 4C.

[0063] In the following, a numerical finite-difference time-domain (FDTD) simulation of the near field distribution and absorption around a nanostructure and a recording mask will be described. The nanostructure may be the second nanostructure referred to in FIGS. 1A, 1B and 2. The nanostructure may also be the second nanostructure 336 of FIGS. 3A-3B and 4A-4B. The recording mask may be the masking layer referred to in FIGS. 1A, 1B and 2. The recording mask may also be the recording mask 338 of FIGS. 3B-3C and 4B-4C. The FDTD simulation is performed to analyse the recording process of a photolithography method according to various embodiments. The recording process may be the second step 300B of FIG. 3B or the second step 400B of FIG. 4B. The simulations take into consideration, a gold nanostructure, surrounded by PDMS from the upper side. In other words, the gold nanostructure is partially embedded in a PDMS film. The gold nanostructure is a nanosphere having a diameter of about 80nm. The gold nanostructure is placed on top of a 20nm-thick chromium film. The chromium film is placed on a SiO₂ substrate. FIGS. 10-13 show the near-field profiles of the gold nanostructure at various cross-sections, when the gold nanostructure is irradiated with a light wave of 800 nm wavelength from above the gold nanostructure. The light wave may be polarized along the X-axis.

[0064] FIG. 10 shows a FDTD simulation 1000 showing an electric-field distribution in the XZ plane for the entire system including the gold nanosphere 1006, the Cr film and the SiO₂ substrate. The X-axis may be denoted by 1004 and the Z-axis may be denoted by 1002.

[0065] FIG. 11 shows a FDTD simulation 1100 showing an electric-field distribution inside the Cr film in the XZ plane in a different color scale. The X-axis may be denoted by 1104 and the Z-axis may be denoted by 1102.

[0066] FIG. 12 shows a FDTD simulation 1200 showing an electric-field distribution on the Cr film surface in the XY plane. The X-axis may be denoted by 1204 and the Y-axis may be denoted by 1202.

[0067] FIG. 13 shows a FDTD simulation 1300 showing an electric-field inside the Cr film at a depth of 5nm from the surface in the XY plane. The X-axis axis may be denoted by 1304 and the Y-axis may be denoted by 1302.

[0068] From FIGS. 10-13, it can be seen that the field enhancement region with maximum up to 11 is mostly distributed beneath the gold nanostructure and the field enhancement region strongly decay with increasing distance from the point of contact between the gold nanostructure and the Cr film. The maximum value and position of the field enhancement regions can be seen from the color map in each of FIGS.10-13 which map the field amplitude normalized to the incident light. Therefore, the maximum enhancement value is the maximum pixel value in the colour map. In FIG. 10, the field maximum as indicated by white colour, is around 11 as can be seen in the colour map. In FIGS.11-13, the colour map is saturated to clearly show the shape of enhancement regions but not their maximum value.

[0069] The cold spot (spot with minimum field) in the middle just beneath the particle (as seen in FIGS. 12, 13) may be compensated by heat-conductance effects in real experiments. Asymmetry of the hot spot may be related to light polarization effects and may be avoided if depolarized or circularly polarized light is used.

[0070] FIG. 14 shows a graph 1400 showing the spectral dependence of the optical energy absorbed in the gold nanostructure and the spectral dependence of the optical energy absorbed in three different areas of the Cr film. The gold nanostructure is also referred herein as the gold particle. The graph 1400 includes a vertical axis 1402 and a horizontal axis 1404. The vertical axis 1402 indicates absorption in arbitrary units (a.u.), while the horizontal axis 1404 indicates the laser wavelength in nanometers. The graph 1400 further includes a first plot 1440, a second plot 1442, a third plot 1444, a fourth plot 1446 and a fifth plot 1448. The first plot 1440 represents the total absorption in the entire system. The second plot 1442 represents the absorption in the gold nanostructure. The third plot 1444 represents the absorption in a first area on the Cr film, the first area having a side length of 40nm. The fourth plot 1446 represents the absorption in a second area on the Cr film, the second area having a side length of 80nm. The fifth plot 1448 represents the absorption in a third area on the Cr film, the third area having a side length of 120nm. It can be seen from the graph 1400, that at longer wavelengths of more than 750 nm, almost all the optical energy is absorbed in the Cr film while almost nothing is absorbed in the gold nanostructure. This can be explained by the strong difference in the optical absorption properties of gold and chromium in this spectral range, as shown in FIGS. 15 and 16.

[0071] FIG. 15 shows a graph 1500 showing the imaginary part of the dielectric function, ϵ'' , of gold as a function of wavelength in the spectral range from 400 to 1000 nm. The graph 1500 has a vertical axis 1502 indicating the imaginary part of the dielectric function, ϵ'' ; and a horizontal axis 1504 indicating wavelength in nanometers.

[0072] FIG. 16 shows a graph 1600 showing the imaginary part of the dielectric function, ϵ'' , of chromium as a function of wavelength in the spectral range from 400 to 1000 nm. The graph 1500 has a vertical axis 1602 indicating the imaginary part of the dielectric function, ϵ'' ; and a horizontal axis 1604 indicating wavelength in nanometers.

[0073] While gold has a minimum in its imaginary part of dielectric function, ϵ'' , (responsible for absorption) with the value below 2 at 800 nm, ϵ'' for chromium constantly grows with the wavelength in this spectral range reaching the value of more than 35 at 800 nm. This can clearly explain why in experiments with laser at about 800 nm, it is possible to melt the chromium film and create holes, while the gold nanostructures remain unaffected and can be reused for multiple recording steps.

[0074] The photolithography method according to various embodiments, may be used not only for nanolithography with ultimately small feature sizes (below 40 nm in current demonstrations), but may also be applied to the design of near-field transducers for heat-assisted magnetic recording (HAMR). As can be seen from FIG. 14, if the irradiation wavelength is chosen to be slightly out of the plasmonic resonance of a transducer, and the optical absorption of the recording medium is significantly higher than that of the plasmonic material of the transducer in the chosen spectral range, it is possible to realize a situation where most of the optical energy is deposited into the recording medium while practically nothing is absorbed in the transducer. For example, more than 95% of the optical energy may be deposited into the recording medium while less than 5% of the optical energy is absorbed in the transducer. For example, the graph 1400 shows that the plasmonic resonance of the gold particle occurs at about a wavelength of 550nm. The absorption of the gold particle decreases sharply at wavelengths larger than 550nm, whereas the absorption of the Cr film reaches a peak at about 650nm. As such, when the light wavelength is more than 650nm, most of the optical energy is absorbed by the Cr film and very little energy is absorbed by the gold particle. In this case, the efficiency of energy deposition into the recording medium may be slightly lower than that at the plasmonic resonance. However, it can still be better to work in this regime since the particle or transducer is not strongly heated and therefore may survive multiple recording cycles. This may help to solve the main challenge of HAMR in relation to the melting of plasmonic transducers during the recording process.

[0075] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus

indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced. It will be appreciated that common numerals, used in the relevant drawings, refer to components that serve a similar or the same purpose.

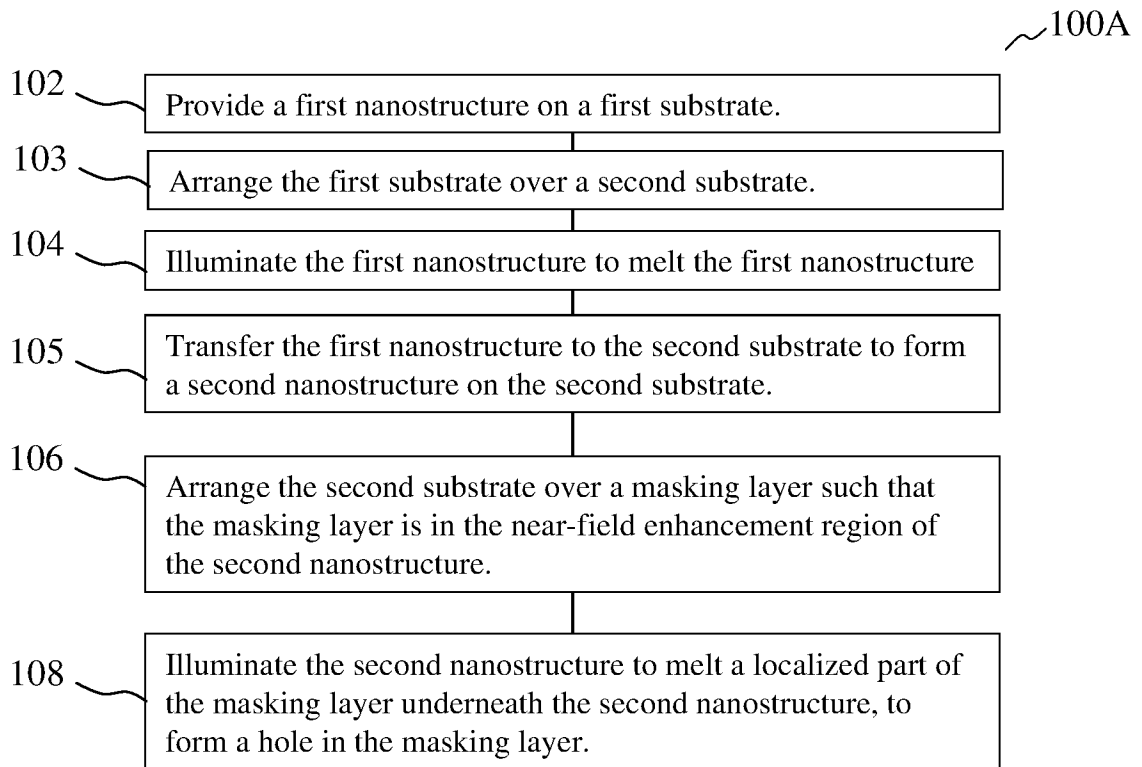
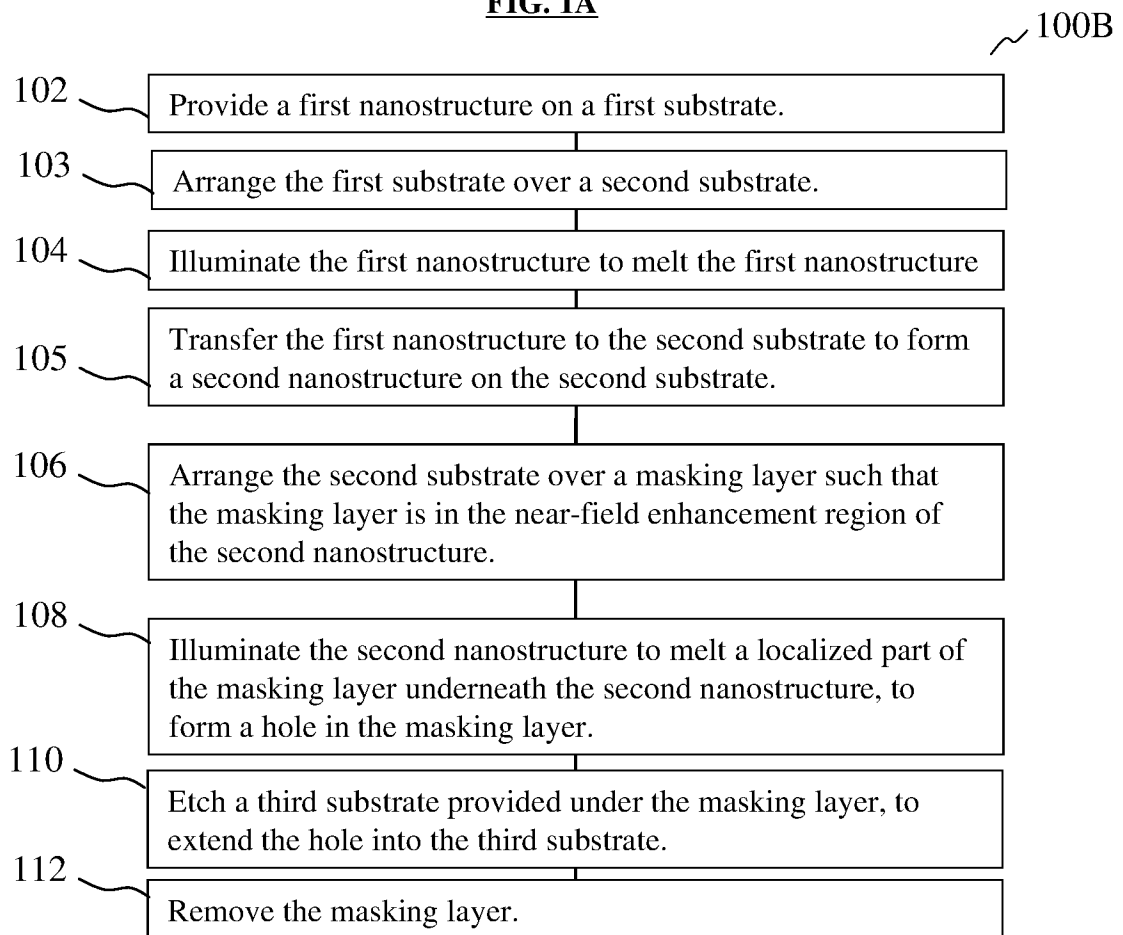
Claims

1. A photolithography method comprising:
 - providing a first nanostructure on a first substrate;
 - arranging the first substrate over a second substrate;
 - illuminating the first nanostructure to melt the first nanostructure;
 - transferring the first nanostructure to the second substrate to form a second nanostructure on the second substrate;
 - arranging the second substrate over a masking layer such that the masking layer is in the near-field enhancement region of the second nanostructure; and
 - illuminating the second nanostructure to melt a localized part of the masking layer underneath the second nanostructure, to form a hole in the masking layer.
2. The photolithography method of claim 1, further comprising:
 - etching a third substrate provided under the masking layer, to extend the hole into the third substrate.
3. The photolithography method of claim 2, further comprising:
 - removing the masking layer.
4. The photolithography method of claim 1, further comprising:
 - providing an interstitial layer over a third substrate, wherein the interstitial layer and the third substrate are provided under the masking layer.
5. The photolithography method of claim 4, further comprising:
 - providing a protective layer between the interstitial layer and the masking layer.
6. The photolithography method of claim 4, further comprising:
 - etching the interstitial layer to extend the hole through the interstitial layer to reach the third substrate.
7. The photolithography method of claim 6, further comprising:

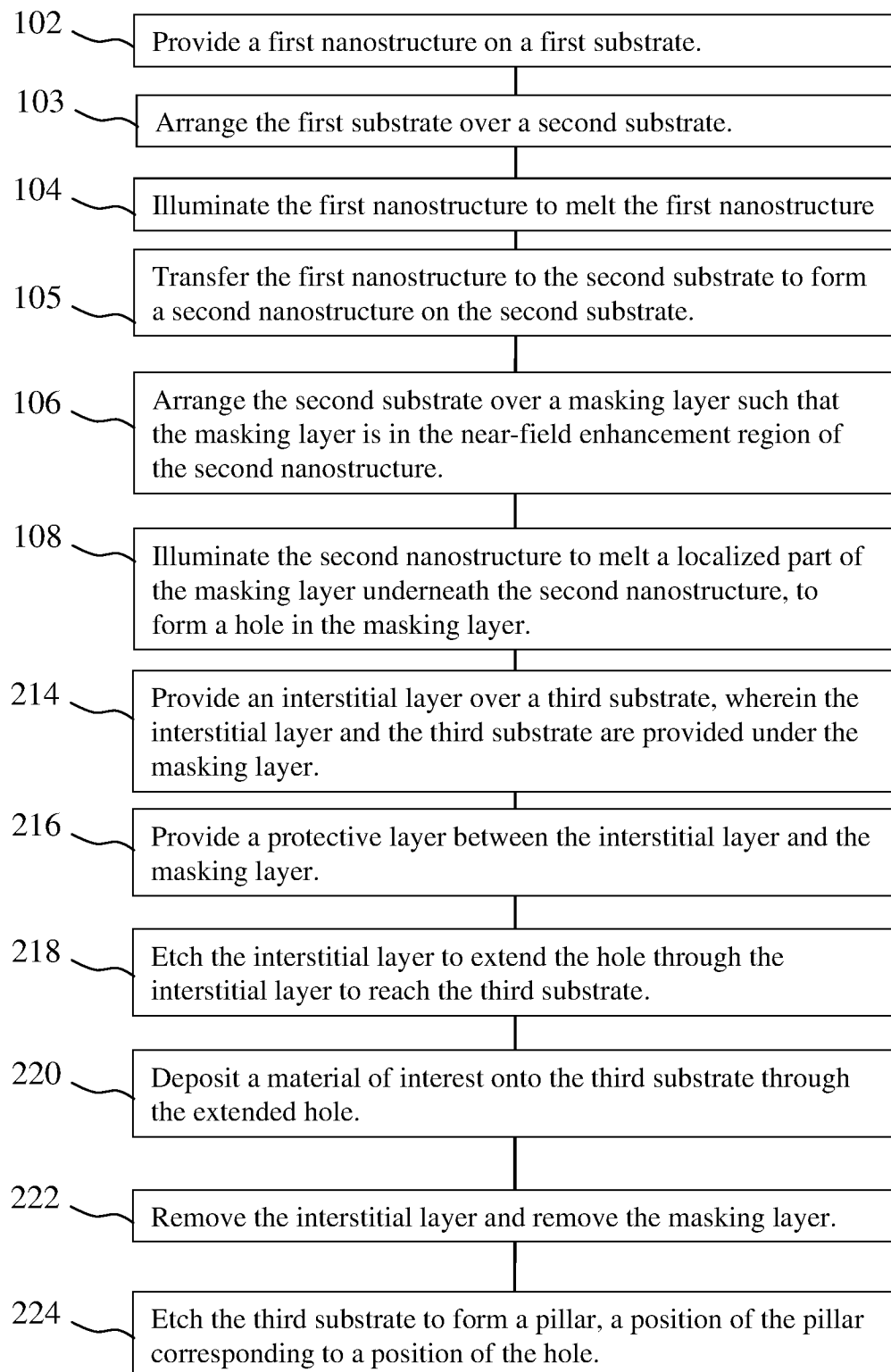
depositing a material of interest onto the third substrate through the extended hole.

8. The photolithography method of claim 7, wherein the material of interest comprises an etching mask material.
9. The photolithography method of claim 7, further comprising:
removing the interstitial layer; and
removing the masking layer.
10. The photolithography method of claim 9, further comprising:
etching the third substrate to form a pillar, a position of the pillar corresponding to a position of the hole.
11. The photolithography method of claim 1, wherein the hole is smaller than the second nanostructure.
12. The photolithography method of claim 1, wherein the second nanostructure is smaller than the first nanostructure.
13. The photolithography method of claim 1, wherein the first nanostructure is provided on the first substrate using any one of photolithography, e-beam lithography, nano-imprint lithography or nanosphere lithography.
14. The photolithography method of claim 1, wherein a plurality of first nanostructures are arranged on the first substrate, wherein the plurality of first nanostructures are illuminated to form a plurality of second nanostructures on the second substrate, wherein illuminating the second substrate forms a plurality of holes in the masking layer on the third substrate.
15. The photolithography method of claim 14, wherein a pattern of the plurality of first nanostructures is replicated on the masking layer as a pattern of the plurality of holes.
16. The photolithography method of claim 1, wherein the first nanostructure comprises plasmonic metals.

17. The photolithography method of claim 1, wherein the second nanostructure is at least substantially spherical or spheroidal.
18. The photolithography method of claim 1, wherein the second substrate comprises a flexible material.
19. The photolithography method of claim 1, wherein at least one of illuminating the first nanostructure or illuminating the second nanostructure comprises providing a visible light.
20. The photolithography method of claim 1, wherein the second nanostructure enhances an optical field in a near-field region of the second nanostructure when the second nanostructure is illuminated.

**FIG. 1A****FIG. 1B**

200

**FIG. 2**

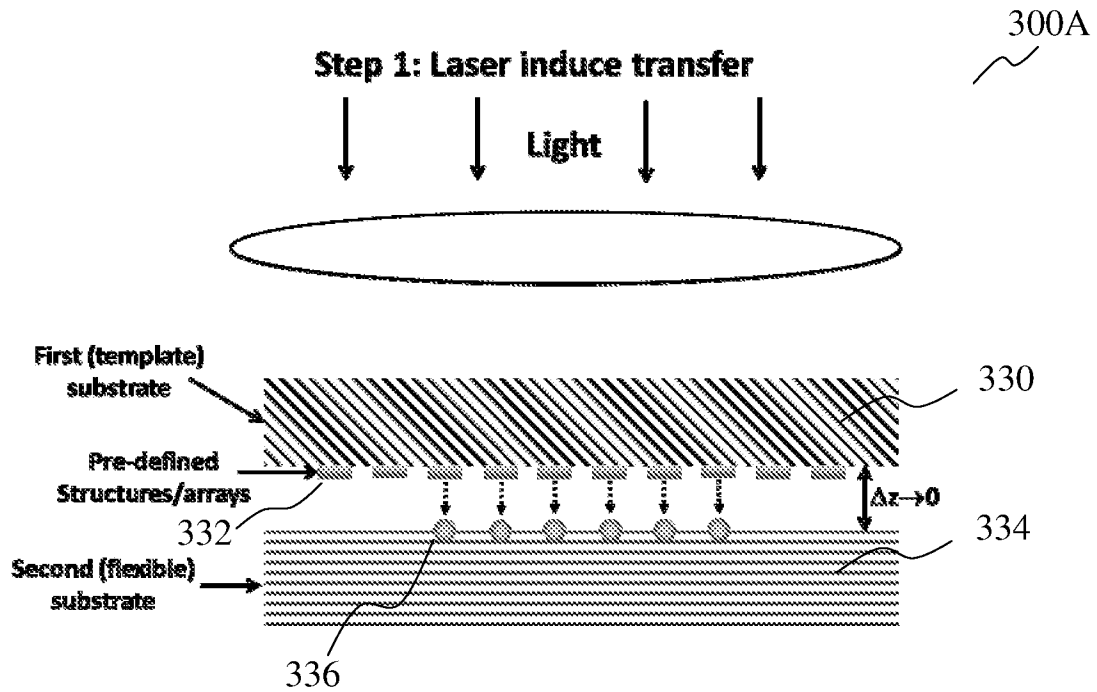


FIG. 3A

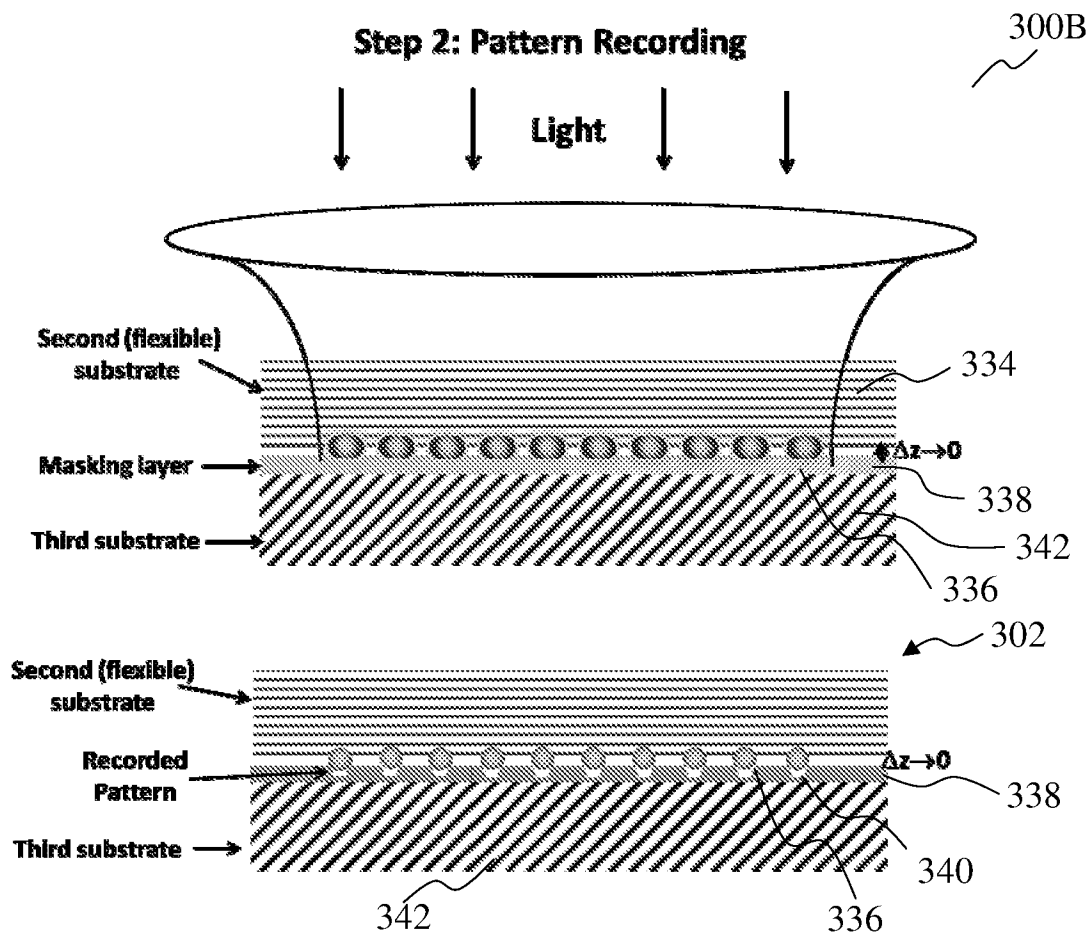


FIG. 3B

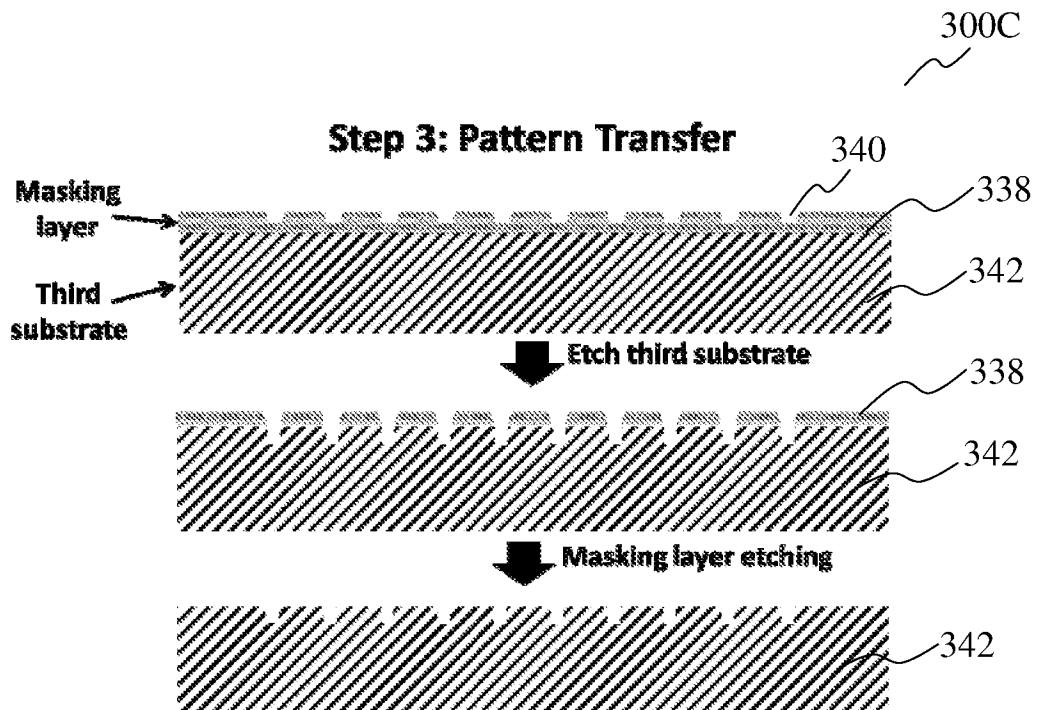
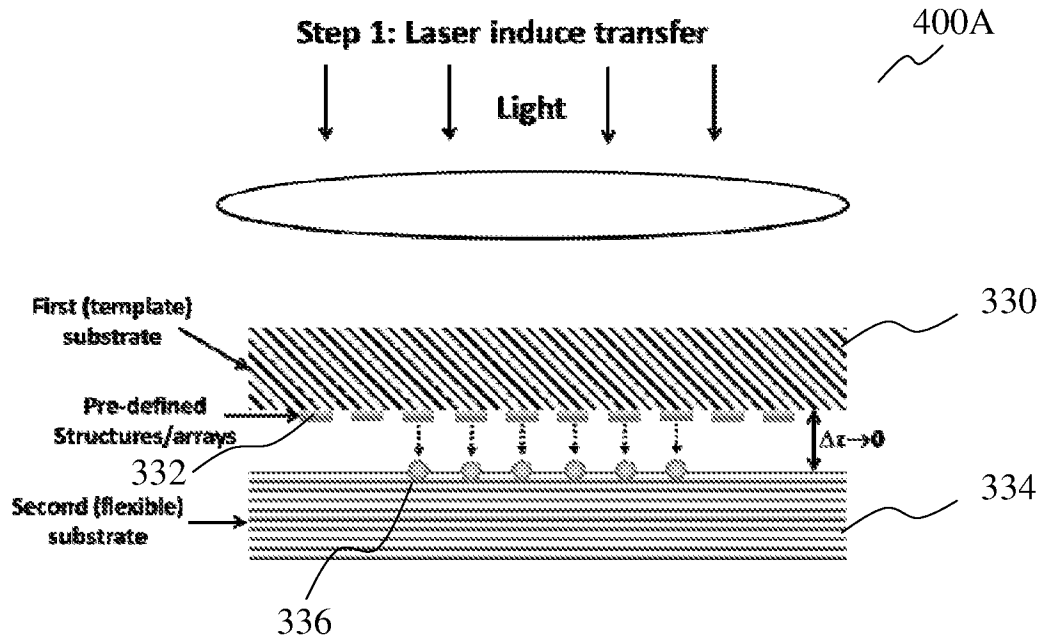
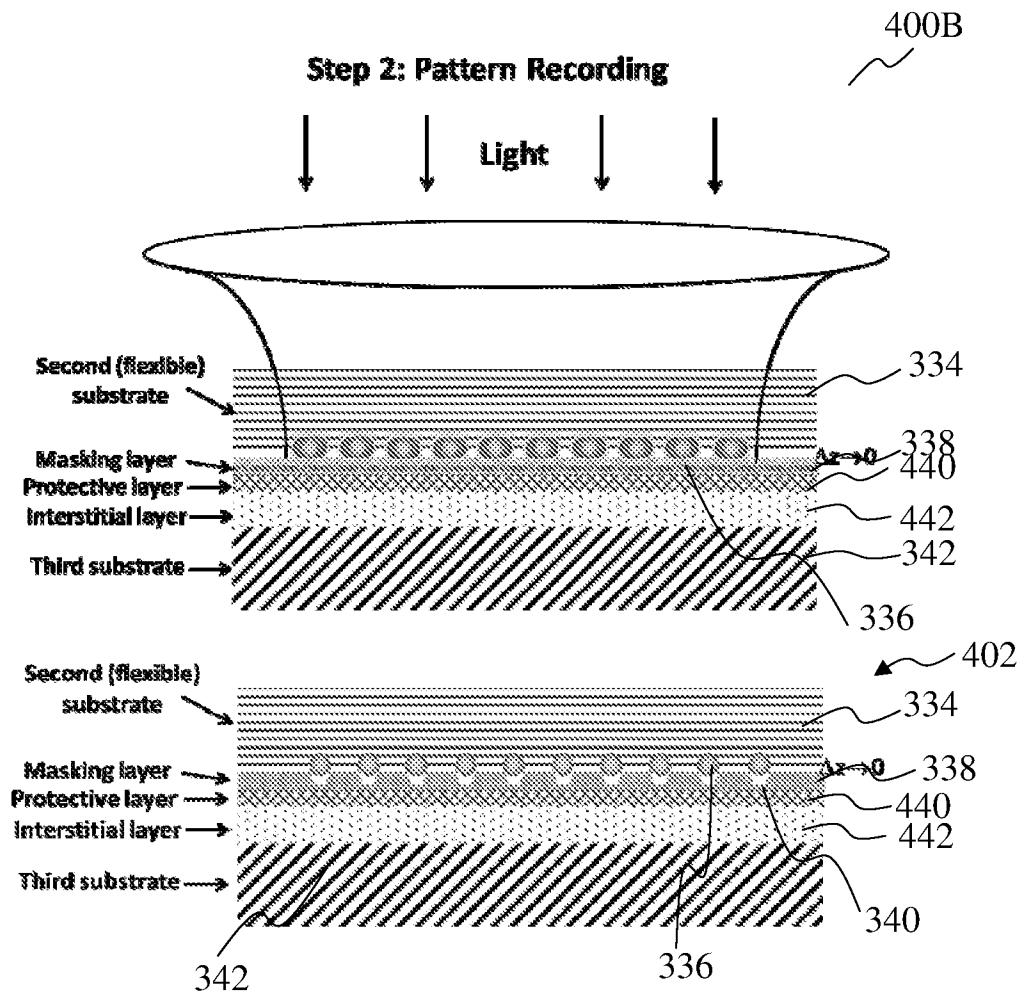


FIG. 3C

**FIG. 4A****FIG. 4B**

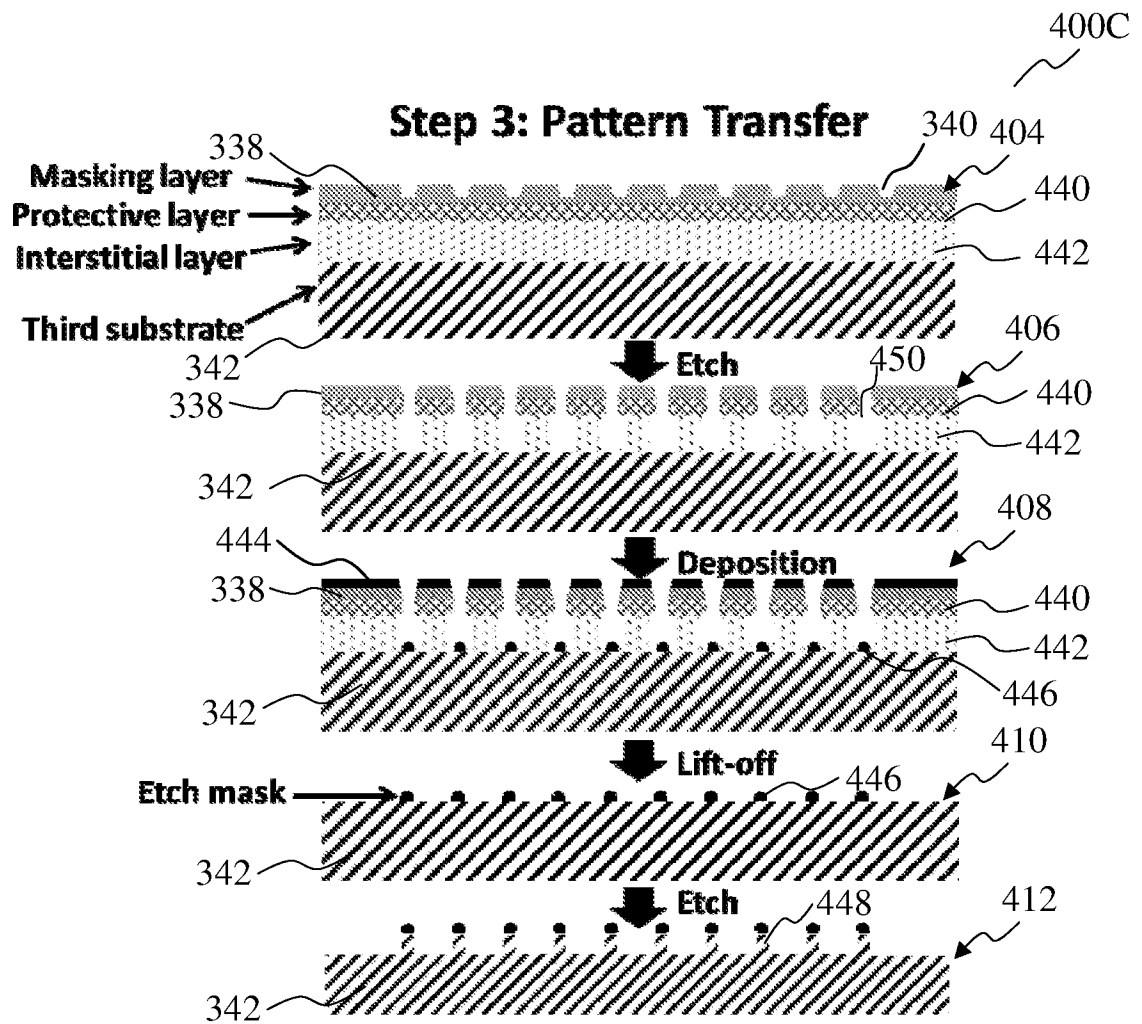
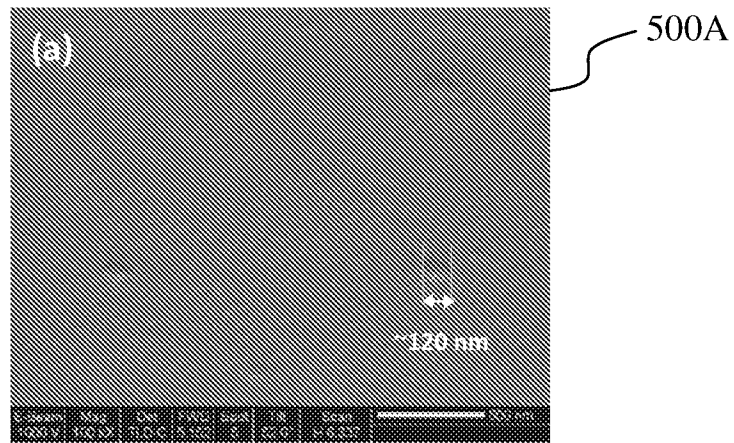
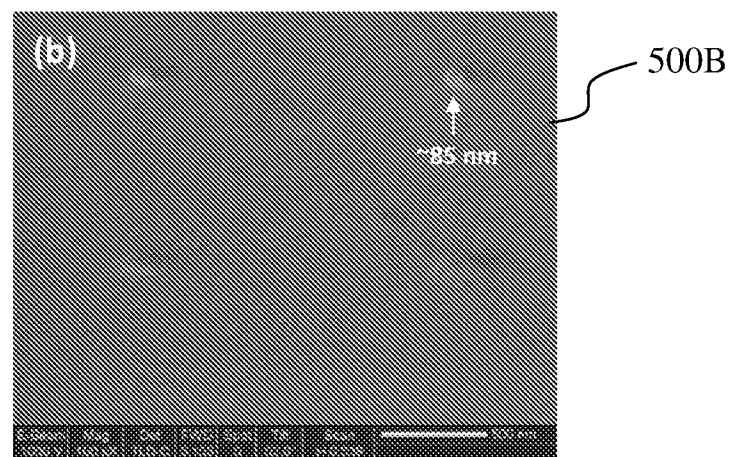
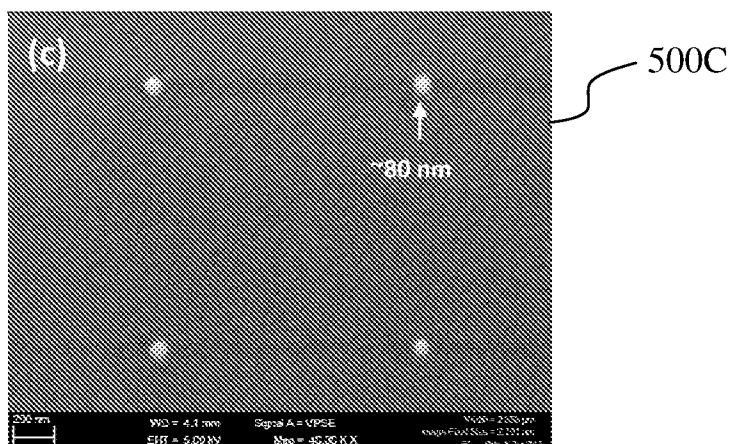


FIG. 4C

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

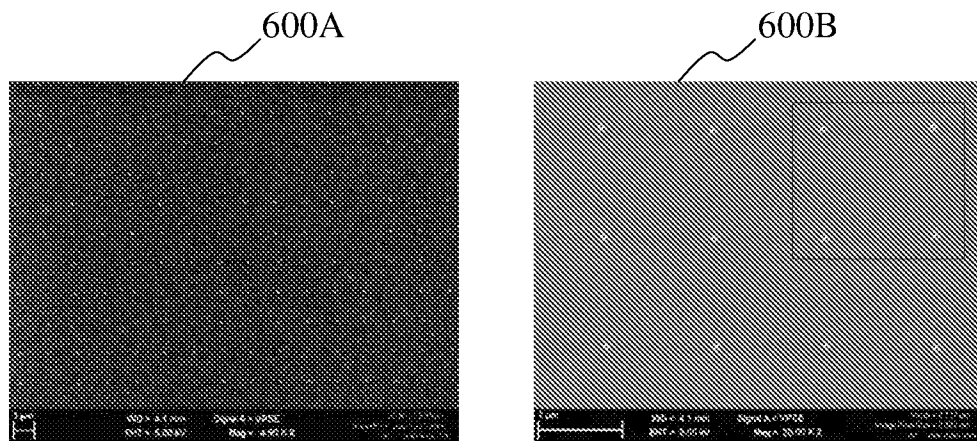


FIG. 6

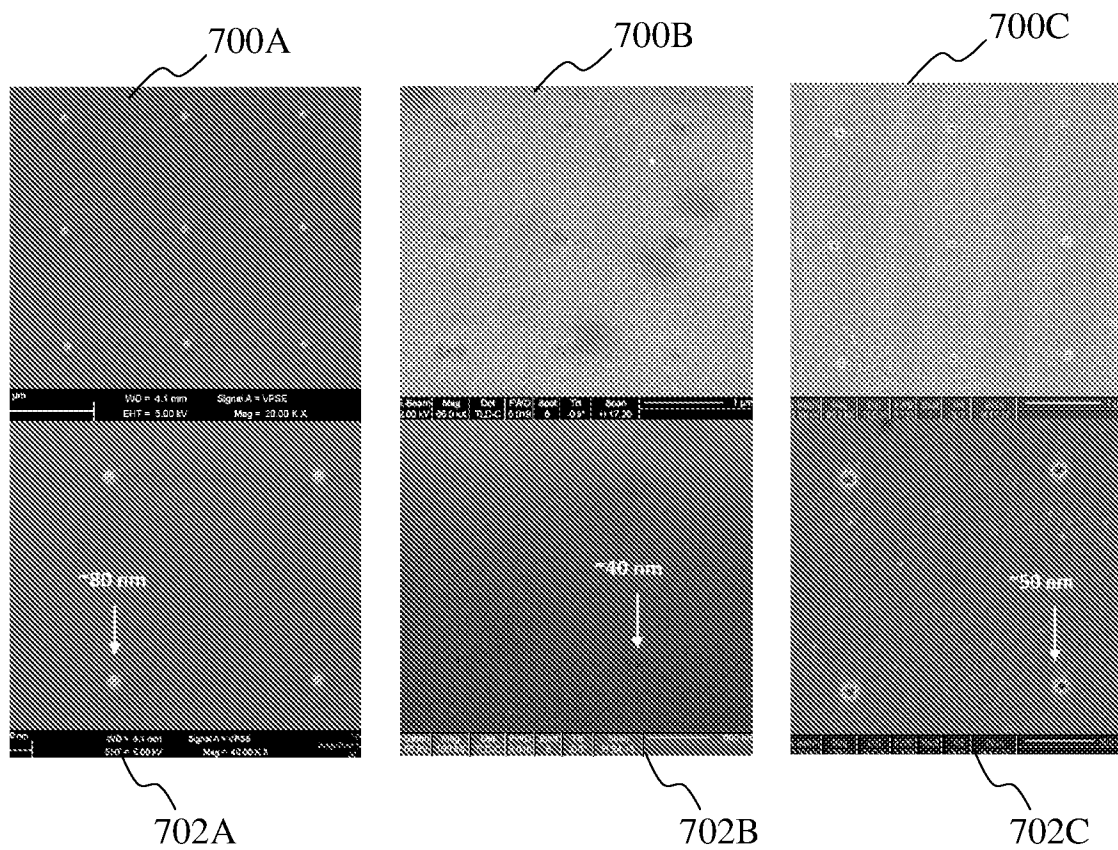
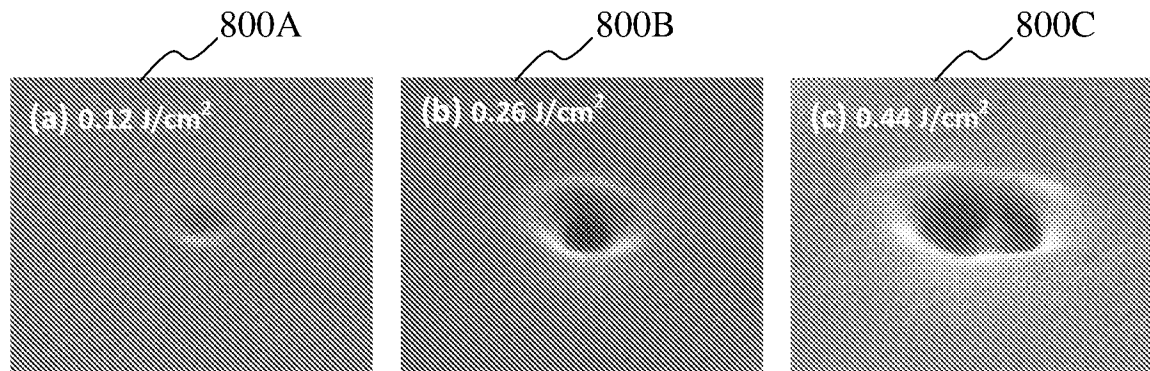
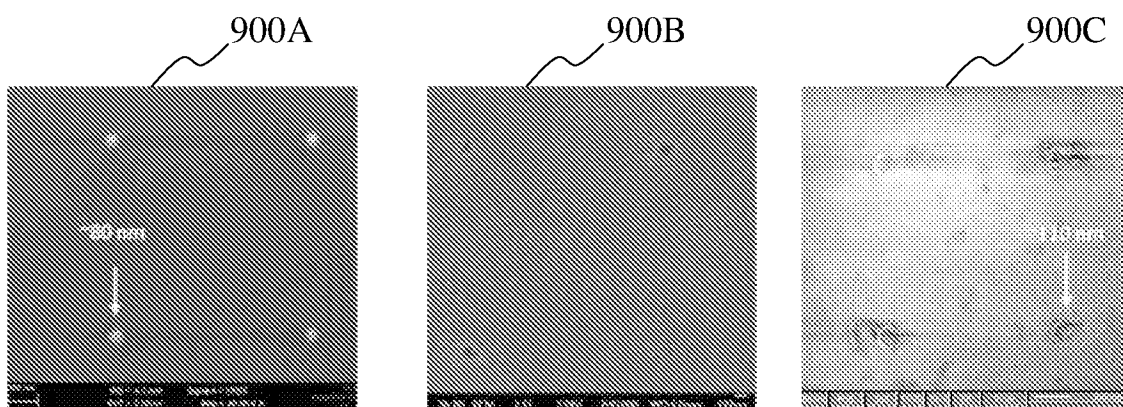


FIG. 7

**FIG. 8**

Au disks on glass
(inverse pattern)

**FIG. 9**

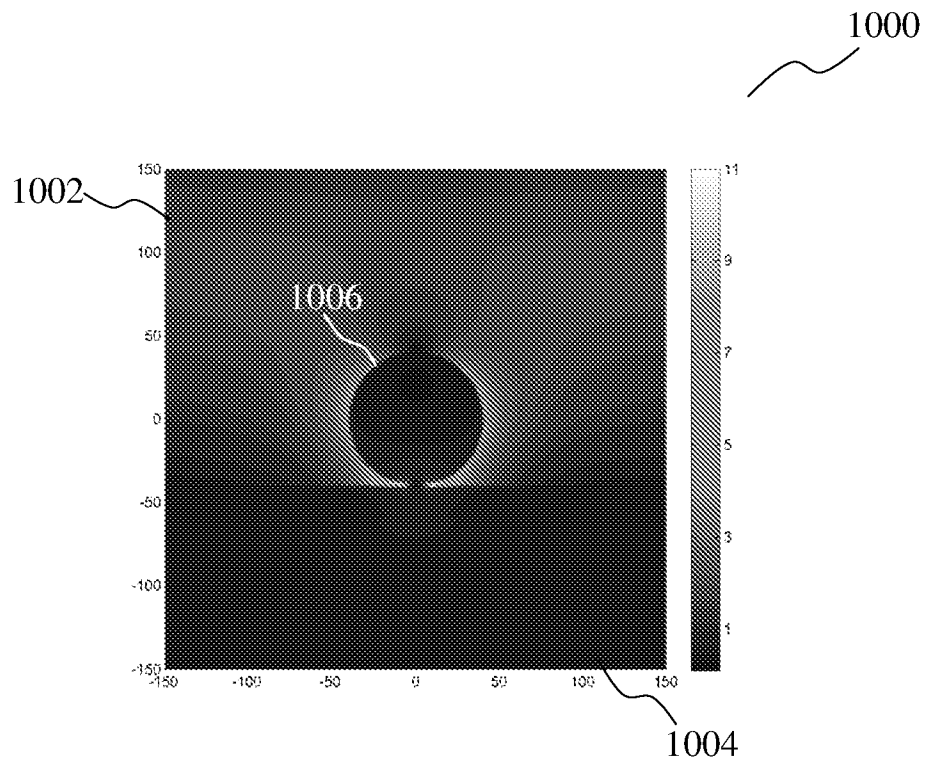


FIG. 10

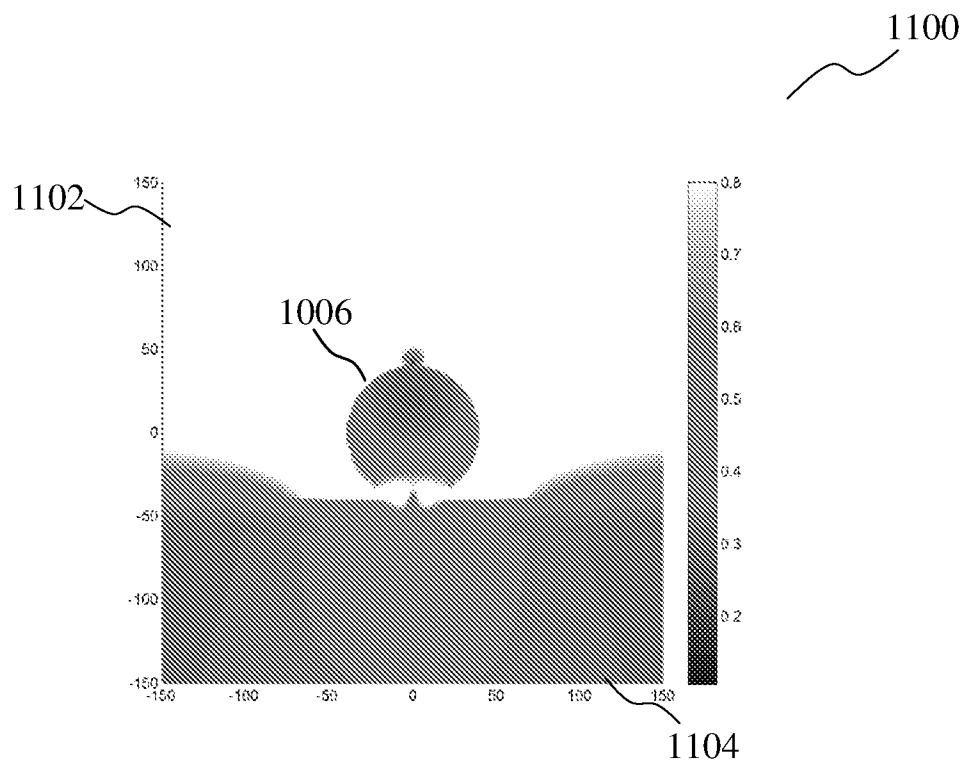


FIG. 11

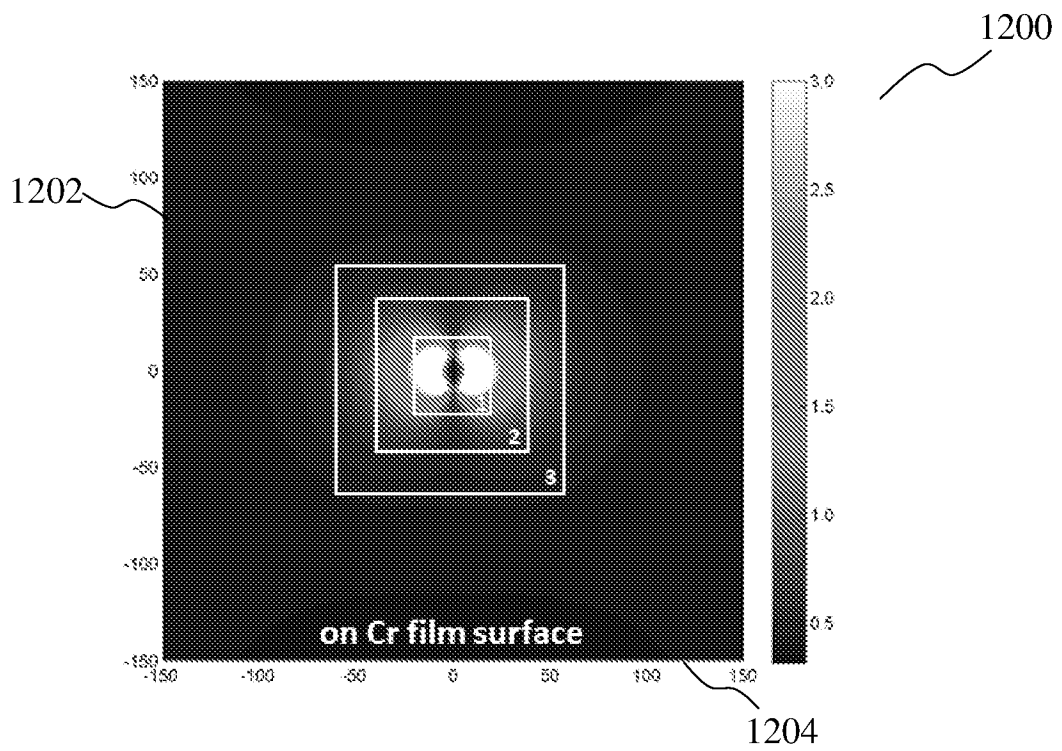


FIG. 12

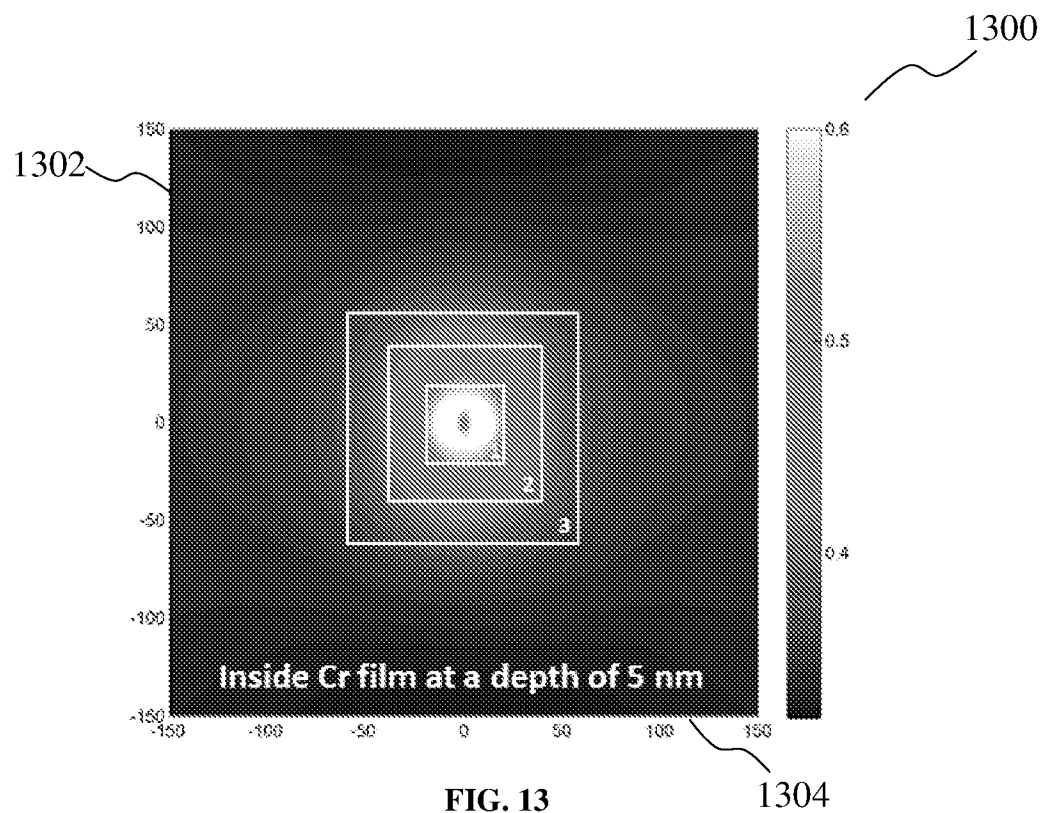


FIG. 13

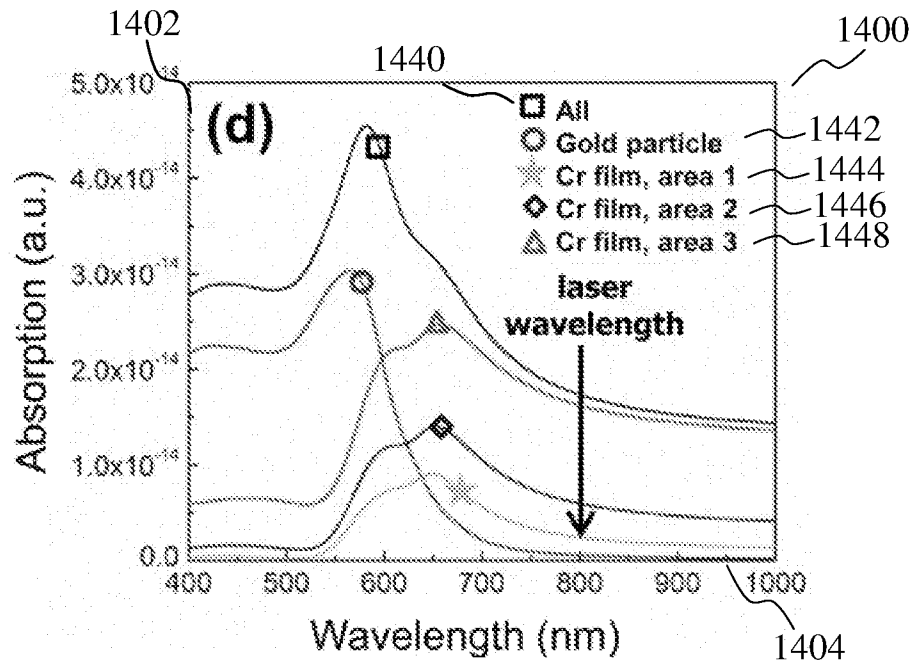


FIG. 14

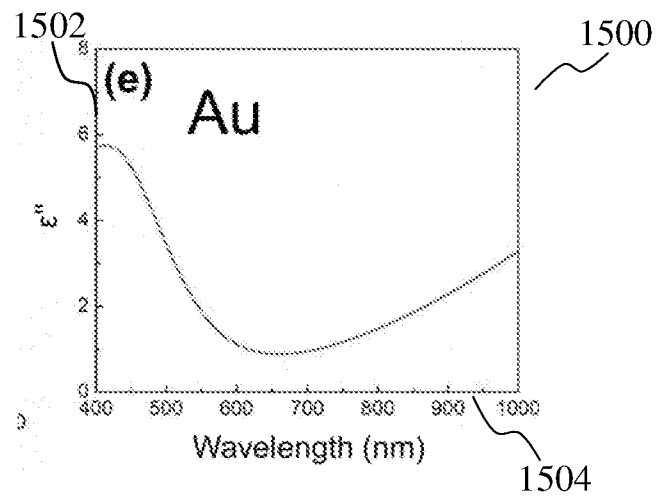


FIG. 15

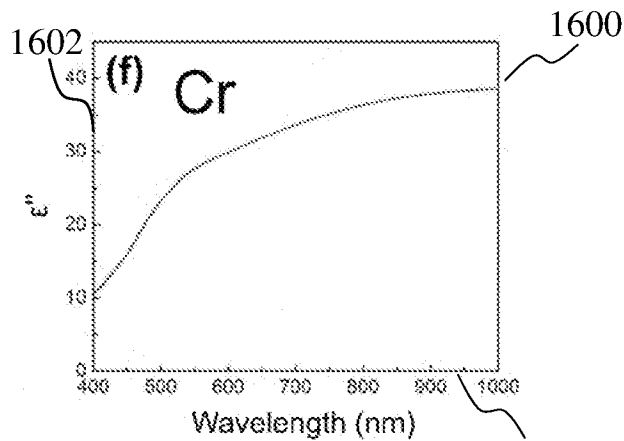


FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050482

A. CLASSIFICATION OF SUBJECT MATTER

See Supplemental Box

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G03F, H01L

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 practicable, search terms used)

Fampat, Epodoc, WPI: lithography, nanoimprint, expose, mask, mold, reticle, pattern, image, 模板, 衬底, 模, second, dual, secondary, lower, upper, two, double, bilayer, 两个, 两层, 双层, 多层, 第二, nanoparticle, nanopillar, nanohole, nanosphere, 纳米颗粒, 纳米丝, 纳米柱, laser, UV, illuminate, light, transfer, plasmonic, near filed and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2007/0128549 A1 (PARK J. H. ET AL.) 7 June 2007 Figs. 1-2, par. [0043]-[0051]	1-19 20
A	US 2009/0109569 A1 (ALBRECHT T. R. ET AL.) 30 April 2009 *Whole document	
A	US 2006/0286368 A1 (ALBRECHT T. R. ET AL.) 21 December 2006 *Whole document	
A	US 2011/0180906 A1 (WESSELS J. ET AL.) 28 July 2011 *Whole document	

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

11/01/2016

(day/month/year)

Date of mailing of the international search report

13/01/2016

(day/month/year)

Name and mailing address of the ISA/SG



Intellectual Property Office of Singapore
51 Bras Basah Road
#01-01 Manulife Centre
Singapore 189554

Email: pct@ipos.gov.sg

Authorized officer

Chen Jiahe (Dr)

IPOS Customer Service Tel. No.: (+65) 6339 8616

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050482**C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 2012/0107583 A1 (XIAO S. G. ET AL.) 3 May 2012 *Whole document	
A	US 2005/0170292 A1 (TSAI H. Y. ET AL.) 4 August 2005 *Whole document	
A	US 2002/0115002 A1 (BAILEY T. ET AL.) 22 August 2002 *Whole document	
A	WO 2013/049367 A2 (ROLITH, INC) 4 Apr 2013 *Whole document	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2015/050482

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2015/050482

Supplemental Box (Classification of Subject Matter)

Int. Cl.

G03F 1/00 (2006.01)

G03F 7/00 (2006.01)

G03F 7/20 (2006.01)

H01L 21/027 (2006.01)

G03F 7/34 (2006.01)

G03F 7/40 (2006.01)