METHOD FOR FORMING THREE-DIMENSIONAL METASURFACE AND THREE-DIMENSIONAL METASURFACE

TECHNICAL FIELD

[0001] The present disclosure generally relates to a method for forming a 3-dimensional metasurface and a three-dimensional metasurface.

BACKGROUND

[0002] Metasurfaces are composed of sub-wavelength structures that control the phase, amplitude, and polarization of light, with typical dimensions in the nanometre range for manipulating visible and telecommunications wavelengths. These metasurfaces are often fabricated using two-dimensional techniques such as electron-beam (e-beam) lithography and photolithography, which limit tunability to two dimensions. Unlocking the third dimension of tunability would enable enhanced functionalities, such as true optical chirality effects, which have been theoretically proposed but remain difficult to achieve in practice due to fabrication challenges. While multiple lithography steps could theoretically create structures with varying heights, misalignment of around 20 nm per step can disrupt periodic order, diminishing effects like chirality. Though proof-of-principle experiments have been conducted in the microwave regime, realizing these designs in the visible light regime requires the development of new fabrication techniques.

[0003] Advanced techniques that avoid multiple alignment steps typically involve directly writing the pattern. For example, focused-ion beam (FIB) lithography is used to pattern metallic films and create three-dimensional structures. However, FIB is a costly process and may induce ion damage to the samples. Two-photon lithography, which can fabricate three-dimensional patterns in polymer resists, has been successfully used to create micrometre-scale optical structures. However, the resolution of two-photon lithography is limited by the wavelength of light used. Grayscale e-beam lithography can overcome this resolution limitation, but both methods are restricted to creating three-dimensional patterns on photo- or electron-sensitive materials, which are typically low-index polymers. This limitation becomes significant when high-index dielectrics are required for optical applications.

[0004] Therefore, there exists a need to provide an improved method for forming a three-dimensional metasurface.

SUMMARY

[0005] According to a first aspect of the present disclosure, a method for a method for forming a three-dimensional metasurface is provided. The method may include forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures including first to N-th nanostructures, wherein N is an integer greater than or equal to 2, each of the plurality of nanostructures including a mask layer and a dielectric layer disposed under the mask layer, wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface includes: (i) removing an i-th mask layer of the i-th nanostructure of the plurality of nanostructures; and (ii) etching an i-th dielectric layer of the i-th nanostructure of the plurality of nanostructure.

[0006] According to a second aspect of the present disclosure, a method for forming a three-dimensional metasurface is provided. The method may include: forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures, each of the plurality of nanostructures including a dielectric layer, wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface further includes: forming an initial mask layer on the two-dimensional metasurface; selectively removing a mask layer of at least one nanostructure of the plurality of nanostructures; and etching a dielectric layer of the at least one nanostructure of the plurality of nanostructure.

[0007] According to a third aspect of the present disclosure, a three-dimensional metasurface is provided. The three-dimensional metasurface may include: a plurality of nanostructures including etched nanostructures and unetched nanostructures, wherein the etched nanostructures have varying heights, and wherein the etched nanostructures are in lateral alignment with the unetched nanostructures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 is a flowchart showing a method for forming a three-dimensional (3D) metasurface (e.g. a 3D nanostructure) according to various embodiments of the present disclosure.

[0009] FIGS. 2A to 2D are block diagrams depicting a method for forming a three-dimensional (3D) metasurface (e.g. a 3D nanostructure) according to various embodiments of the present disclosure.

[00010] FIG. 3 shows atomic force microscopy (AFM) images and height profiles of nanostructures fabricated by the method of FIGS. 2A to 2D.

[00011] FIG. 4 shows a 3D metasurface according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[00012] Embodiments described below in the context of a method are analogously valid for the respective element, device, apparatus, or system, 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, and a part of one implementation may be combined with a part of another implementation.

[00013] It should be understood that the singular terms "a", "an", and "the" include plural references unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise.

[00014] It will be further understood that the terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including"), and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that "comprises," "has," "includes" or "contains" one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[00015] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about," "substantially", is not limited to the precise value specified

but within tolerances that are acceptable for operation of the embodiment for an application for which it is intended. In some instances, the approximating language may correspond to the precision of an instrument for measuring the value.

[00016] As used herein, the term "three-dimensional (3D) metasurface" may refer to a 3D material or structure designed to manipulate electromagnetic waves (such as light, sound, or other radiation) through intricate and tailored geometric arrangements at the subwavelength scale in three dimensions. While conventional metasurfaces are typically thin (two-dimensional) layers that modify wave properties through surface interactions (e.g. x- and y-directions), 3D metasurfaces extend this concept into the third dimension (e.g. z-direction), introducing an additional level of complexity and control. This third dimension enables more advanced and precise manipulation of wave propagation, interaction, and behaviour, allowing for enhanced functionalities in a wide range of applications.

[00017] According to various non-limiting embodiments, the present disclosure describes a new method to fabricate a three-dimensional (3D) dielectric metasurface from a two-dimensional (2D) metasurface for high performance nanophotonic devices. This approach may use only a single lithography (e.g. e-beam, focused ion beam (FIB), photolithography, etc.) step to define lateral positions (e.g. in the x- and y- directions or in the x-y surface) and shape of the meta-atoms (e.g. nanopillars or nanostructures) of the 2D metasurface, represented by a thin metal hard mask layer. The metallic mask on top of the meta-atoms may be selectively removed by electrochemical oxidation, using an atomic force microscopy (AFM) tip as one electrode to contact the metallic mask. A bias may be applied to electrochemically oxidise the metallic mask which dissolves into an electrolyte. A subsequent etching step may be conducted to etch the exposed nanopillars or nanostructures to a required height (e.g. in the z-direction).

[00018] According to various non-limiting embodiments, this process may be repeated N times to obtain N+1 different height profiles of nanopillars or nanostructures. The nanoscale positional control and feedback loop of the AFM may allow control of the force to nano-newton levels. Precise force control may be required to ensure good electrical contact between tip and the metallic mask while preventing damage to the underlying dielectric metasurface. In addition, the choice of metal compositions for hard mask may be also critical to ensure clean removal of the metallic mask without leaving any residue. Moreover, by using the same tip for imaging, the process in-situ may be achieved which locate specific nanopillar(s) or nanostructure(s) to be modified. This process may require only one lithography step, thus

avoiding the need for multiple alignment steps to achieve multiple heights. This may eliminate any misalignment errors or deviations that disrupt periodicity and may diminish optical effects. The spatial resolution may be determined by the AFM tip diameter (e.g. of about 50 nm). The present method or process may be applied to fabricate 3D dielectric metasurfaces (i.e. nanopillars or nanostructures with multiple heights) that provide improved functionalities over their 2D counterparts, for example, to achieve true optical chirality effects, generation of optical angular momentum, and realisation of a parity-time symmetry-broken optical system.

[00019] The present method may use only a single lithography step to define lateral positions of all meta-atoms in the 2D metasurface, while additional AFM and RIE etching steps (e.g. reversed electrochemical process) may be used to define their heights to form the 3D surface. The present method may result in zero misalignment errors in lateral position of meta-atoms with different heights that otherwise cannot be achieved using conventional multiple-step lithography approaches. In other words, no alignment step may be required between defining each height and therefore no lateral misalignment may be occurred. The mask layers may be completely or cleanly removed by the chemical wet etch step. The present method may be applied to pattern on sensitive and flexible substrates. The present method may fabricate chiral structures with out-of-plane symmetry breaking without lateral misalignments which would diminish its optical effect. The present fabrication technique may unlock another dimension (e.g. z-direction) when designing functional metasurfaces, which may find broad applications in high performance flat optics, optical chirality, and nonlinear optics. The present method may have a commercial potential in metasurface designs, providing an additional parameter of height to manipulate and shape the wavefront of light. Applications may include true chiral metasurfaces for chiral chemical, biological sensing and imaging, and anti-counterfeiting features.

[00020] The following examples pertain to various aspects of the present disclosure.

[00021] Example 1 is a method for forming a three-dimensional metasurface, including: forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures including first to N-th nanostructures, wherein N is an integer greater than or equal to 2, each of the plurality of nanostructures including a mask layer and a dielectric layer disposed under the mask layer, wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface includes: (i) removing an i-th mask layer of the i-th nanostructure of the plurality of

nanostructures; and (ii) etching an i-th dielectric layer of the i-th nanostructure of the plurality of nanostructure.

[00022] In Example 2, the subject matter of Example 1 may optionally include that the forming a three-dimensional metasurface based on a two-dimensional metasurface further includes: removing a j-th mask layer of the j-th nanostructure of the plurality of nanostructures; and etching a j-th dielectric layer of the j-th nanostructure of the plurality of nanostructure, wherein an i-th height of the etched i-th nanostructure is different from a j-th height of the etched j-th nanostructure.

[00023] In Example 3, the subject matter of Example 1 or 2 may optionally include: repeating the steps (i) and (ii) to form M etched nanostructures based on M nanostructures of the plurality of nanostructures, wherein M is an integer, equal to or greater than 2, and less than or equal to N.

[00024] In Example 4, the subject matter of Example 3 may optionally include that heights of the M etched nanostructures vary from one another.

[00025] In Example 5, the subject matter of any of Examples 1 to 4 may optionally include that electrochemical oxidation is used for removing the respective mask layer of the plurality of nanostructures.

[00026] In Example 6, the subject matter of Example 5 may optionally include that a bias in a range of 1.0 to 3.0 V is applied to oxidize the respective mask layer of the plurality of nanostructures and a solution is subsequently used to dissolve the oxidized respective mask layer of the plurality of nanostructures.

[00027] In Example 7, the subject matter of Example 5 or 6 may optionally include that a conductive atomic force microscopy (AFM) tip is used for removing the respective mask layer of the plurality of nanostructures.

[00028] In Example 8, the subject matter of Example 7 when dependent from Example 3 or Example 4 may optionally include that the AFM tip is used for removing all mask layers of the M nanostructures of the plurality of nanostructures.

[00029] In Example 9, the subject matter of Example 7 or 8 may optionally include that a setpoint force of the AFM tip is in a range of nano-newton levels, particularly, in a range of 10 to 50 nano-newtons.

[00030] In Example 10, the subject matter of any of Examples 1 to 9 may optionally include that the two-dimensional metasurface is fabricated by: forming an initial mask layer on an

initial dielectric layer; etching the initial dielectric layer through the initial mask layer by lithography to form the 2-dimential metasurface

[00031] In Example 11, the subject matter of Example 10 may optionally include that the method for forming the three-dimensional metasurface includes one single lithography step being the lithography for forming the 2-dimential metasurface.

[00032] In Example 12, the subject matter of Example 10 or 11 may optionally include that the lithography includes reactive ion etch (RIE) process.

[00033] In Example 13, the subject matter of any of Examples 10 to 12 may optionally include that the initial dielectric layer is deposited on a silicon dioxide (SiO_2) substrate.

[00034] In Example 14, the subject matter of any of Examples 10 to 13 may optionally include that the initial mask layer includes a metallic layer.

[00035] In Example 15, the subject matter of any of Examples 10 to 14 may optionally include that the initial dielectric layer includes silicon, titanium dioxide, silicon nitride, or other group III-V or II-VI semiconductors.

[00036] In Example 16, the subject matter of any of Examples 1 to 15 may optionally include removing mask layers of unetched nanostructures of the plurality of nanostructures by a chemical wet etch to obtain the 3-dimentsion metasurface.

[00037] Example 17 is a method for forming a three-dimensional metasurface, including: forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures, each of the plurality of nanostructures including a dielectric layer, wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface further includes: forming an initial mask layer on the two-dimensional metasurface; selectively removing a mask layer of at least one nanostructure of the plurality of nanostructures; and etching a dielectric layer of the at least one nanostructure of the plurality of nanostructure.

[00038] Example 18 is a three-dimensional metasurface including: a plurality of nanostructures including etched nanostructures and unetched nanostructures, wherein the etched nanostructures have varying heights, and wherein the etched nanostructures are in lateral alignment with the unetched nanostructures.

[00039] In Example 19, the subject matter of Example 18 may optionally include that the unetched nanostructures have a same height.

[00040] In Example 20, the subject matter of Example 18 or 19 may optionally include that the three-dimensional metasurface is chiral.

[00041] FIG. 1 is a flowchart showing a method 100 for forming a three-dimensional (3D) metasurface (e.g. a 3D nanostructure) according to various embodiments of the present disclosure. According to various non-limiting embodiments, the method 100 may include: at step 102, forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures including first to N-th nanostructures, wherein N is an integer greater than or equal to 2, each of the plurality of nanostructures including a mask layer and a dielectric layer disposed under the mask layer. The forming a three-dimensional metasurface based on a two-dimensional metasurface may include: (i) removing an i-th mask layer of the i-th nanostructure of the plurality of nanostructures, $1 \leq i \leq N$; and (ii) etching an i-th dielectric layer of the i-th nanostructure of the plurality of nanostructures. In other words, the method 100 may include selectively removing a mask layer of a nanostructure of the plurality of nanostructures; and etching a dielectric layer of the nanostructure of the plurality of nanostructure. The dielectric layer of the etched nanostructure of the plurality of nanostructures may consequently have a height less than its original height. Assuming that the plurality of nanostructures have substantially equal heights, the dielectric layer of the etched nanostructure of the plurality of nanostructure may have a height less than heights of the remaining nanostructures (i.e. the (N-1) non-etched nanostructures of the plurality of nanostructures. In the context of various embodiments, the unetched nanostructures refer to the nanostructures that serve as the reference or bases for the etching process while the etched nanostructures may be fabricated by etching away material from the surface of the corresponding nanostructures.

[00042] According to some embodiments, the method 100 may include (i) removing mask layers of selected multiple nanostructures of the plurality of nanostructures; and (ii) etching dielectric layers of the selected multiple nanostructures of the plurality of nanostructures. In other words, the method 100 may include selectively removing mask layers of multiple nanostructures of the plurality of nanostructures; and simultaneously etching dielectric layers of the multiple nanostructure of the plurality of nanostructure. The selected multiple nanostructures may include adjacent nanostructures or non-adjacent (e.g. separate or distant) multiple nanostructures. The adjacent nanostructures may be operated (e.g. to remove mask layers and to etch dielectric layers) by a single tool (e.g. a single atomic force microscopy

(AFM) tip as described hereinafter). The non-adjacent (e.g. separate or distant) multiple nanostructures may be simultaneously operated by multiple tools (e.g. multiple AFM tips) or sequentially operated by a single tool (e.g. a single AFM tip).

[00043] According to alternative embodiments, the method for forming a three-dimensional metasurface may include: forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface includes a plurality of nanostructures, each of the plurality of nanostructures including a dielectric layer. In other words, the plurality of nanostructures may include only dielectric layers but not mask layers in these alternative embodiments. Accordingly, the forming a three-dimensional metasurface based on a two-dimensional metasurface may further include: forming an initial mask layer on the two-dimensional metasurface; selectively removing a mask layer of at least one nanostructure of the plurality of nanostructures; and etching a dielectric layer of the at least one nanostructure of the plurality of nanostructure. The initial mask layer may be formed both on the plurality of nanostructures and the substrate (e.g. the spacings between nanostructures).

[00044] According to various non-limiting embodiments, the forming a three-dimensional metasurface based on a two-dimensional metasurface may further include: removing a j-th mask layer of the j-th nanostructure of the plurality of nanostructures, $1 \leq j \leq N$ and $j \neq i$; and etching a j-th dielectric layer of the j-th nanostructure of the plurality of nanostructure, wherein an i-th height of the etched i-th nanostructure is different from a j-th height of the etched j-th nanostructure. In other words, the method 100 may further include removing a further mask layer of a further nanostructure of the plurality of nanostructures; and etching a further dielectric layer of the further nanostructure of the plurality of nanostructure. A further height of the etched further nanostructure may be different from the height of the etched nanostructure as described above. The present method 100 may provide an approach of individually and selectively etching nanostructure(s) of the plurality nanostructures to achieve (varying) pre-determined height(s). The present method 100 may not require additional lithography, which may require alignment between masks and nanostructures to be etched. Without the implementation of absolute alignment, the accuracy and precision of the nanostructure patterning may be compromised, affecting the performance and functionality of the final product.

[00045] According to various non-limiting embodiments, the method 100 may further include repeating the steps (i) and (ii) to form M etched nanostructures based on M

nanostructures of the plurality of nanostructures, wherein M is an integer, equal to or greater than 2, and less than or equal to N. In other words, the method 100 may repeat etching more (i.e. $2 \leq M < N$) or all (i.e. $M = N$) nanostructures of the plurality of nanostructures. Heights of the M etched nanostructures may vary from one another. In some embodiments, the method 100 may include (iteratively) repeating the steps (i) and (ii) to further etch the i-th and/or j-th nanostructures based on the etched i-th and/or j-th nanostructures. Alternatively or additionally, the plurality of nanostructures (or including the previously etched nanostructures) may be simultaneously etched as described herein.

[00046] According to various non-limiting embodiments, electrochemical oxidation may be used for removing the respective mask layer of the plurality of nanostructures to be etched. A bias in a range of 1.0 to 3.0 V, or specifically 2.0 to 2.5 V depending on the oxidation potential of the material used, may be applied to oxidize the respective mask layer of the plurality of nanostructures through electrodes and a solution (e.g. an electrolyte) may be subsequently used to dissolve the oxidized respective mask layer of the plurality of nanostructures. Any salt solution that dissolves the metallic mask layer may be applicable in the present method. In an example, the two-dimensional (2D) metasurface may be submerged into the solution.

[00047] According to various non-limiting embodiments, a conductive atomic force microscopy (AFM) tip may be used for removing the respective mask layer of the plurality of nanostructures. That is, the AFM tip may be used as an electrode to oxidize the respective mask layer of the plurality of nanostructures. The AFM tip may image in-situ while applying bias with high spatial resolution and precision (to the order of tip diameter, e.g. about 50 nm). The same AFM tip may be used for removing all mask layers of the M nanostructures of the plurality of nanostructures. Alternatively, multiple AFM tips (e.g. M AFM tips) may be (e.g. respectively) used for removing all mask layers of the M nanostructures of the plurality of nanostructures. A setpoint force of the AFM tip may be in a range of nano-newton levels, particularly, in a range of 10 to 50 nano-newtons or specifically 10 to 20 nano-newtons.

[00048] According to various non-limiting embodiments, the 2D metasurface may be fabricated by: forming an initial mask layer on an initial dielectric layer; etching the initial dielectric layer through the initial mask layer by lithography to form the 2D metasurface. It should be appreciated that the method of fabricating the 2D metasurface is not limited to the above, other known methods for fabricating the 2D metasurface are also included in the present method 100.

[00049] According to various non-limiting embodiments, the method 100 for forming the 3D metasurface including one single lithography step being the lithography for forming the 2-dimensional metasurface. The lithography may include reactive ion etch (RIE) process.

[00050] According to various non-limiting embodiments, the initial dielectric layer may be deposited on a silicon dioxide (SiO_2) substrate. Any insulating material (e.g. silicon (Si), sapphire, aluminium oxide (Al_2O_3), quartz, glass, or polymer) may be used as a substrate. The initial dielectric layer may include silicon, titanium dioxide, silicon nitride, or other group III-V or II-VI semiconductors. The initial mask layer may include a metallic layer. According to various non-limiting embodiments, the metallic layer may include a chromium layer. It should be appreciated the metallic layer is not limited to chromium, at least gold (Au), platinum (Pt), Nickel (Ni) and other Group 6 (VIb) metal elements including molybdenum (Mo), Tungsten (W) are included in the 2D metasurface.

[00051] According to various non-limiting embodiments, the method 100 may further include removing mask layers of unetched nanostructures of the plurality of nanostructures by a chemical wet etch to obtain the 3-dimentsion metasurface. According to the alternative embodiments as described hereinbefore, the method may further include removing mask layers of unetched nanostructures of the plurality of nanostructures and mask layers on the substrate by a chemical wet etch to obtain the 3-dimension metasurface.

[00052] According to various non-limiting embodiments, an etching ratio of the mask layer to the dielectric layer may be equal to or greater than 15:1, or larger than the aspect ratio of the nanostructures. The 2-dimension metasurface may include nanopillars or nanostructures having an aspect ratio of equal to or greater than 10 to 1.

[00053] FIGS. 2A to 2D are block diagrams depicting a method 200 for forming a three-dimensional (3D) metasurface (e.g. a 3D nanostructure) according to various embodiments of the present disclosure.

[00054] FIG. 3 shows AFM images and height profiles of nanostructures fabricated by the method 200 of FIGS. 2A to 2D. Scale bars 31, 32, 33, shown in the AFM images of FIG. 3 represent 200 nm.

[00055] The AFM tip shown in FIGS. 2A to 2D and 3 may have a diameter of about 50 nm.

[00056] The method 200 may include similar steps of the method 100 as described above in connection to FIG. 1, and therefore, features that are described in the context of the method 100 may correspondingly be applicable to the same or similar features in the method 200 and

vice versa. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of the method 100 may correspondingly be applicable to the same or similar feature in the method 200 and *vice versa*.

[00057] According to various non-limiting embodiments, the method 200 may include forming a three-dimensional (3D) metasurface 20a based on a two-dimensional (2D) metasurface 20, wherein the two-dimensional metasurface 20 includes a plurality of nanostructures 210, 220, 230, 240, each of the plurality of nanostructures 210, 220, 230, 240, including a mask layer (211 for the nanostructure 210, 221 for the nanostructure 220, 231 for the nanostructure 230, 241 for the nanostructure 240) and a dielectric layer (213 for the nanostructure 210, 223 for the nanostructure 220, 233 for the nanostructure 230, 243 for the nanostructure 240) disposed under the mask layer (211 for the nanostructure 210, 221 for the nanostructure 220, 231 for the nanostructure 230, 241 for the nanostructure 240). It shall be appreciated that although FIG. 2A shows cross-sections of four nanostructures 210, 220, 230, 240, the two-dimensional metasurface 20, for example, an array of subwavelength nanostructures, also called meta-atoms, may include any number of nanostructures in accordance with the design requirements.

[00058] According to various non-limiting embodiments, the 2D metasurface 20 may include a substrate 270 (e.g. silicon dioxide (SiO_2)), that is, the plurality of nanostructures 210, 220, 230, 240, are deposited on the substrate 270. The dielectric layers (213 for the nanostructure 210, 223 for the nanostructure 220, 233 for the nanostructure 230, 243 for the nanostructure 240) of the plurality of nanostructures 210, 220, 230, 240 may include silicon, titanium dioxide, silicon nitride, or other group III-V or II-VI semiconductors. Any dielectric material may be included in the present method. The mask layers (211 for the nanostructure 210, 221 for the nanostructure 220, 231 for the nanostructure 230, 241 for the nanostructure 240) of the plurality of nanostructures 210, 220, 230, 240 may include a metallic layer. According to various non-limiting embodiments, the metallic layer may include a chromium layer. It should be appreciated the metallic layer is not limited to chromium, at least other Group 6 (VIb) metal elements including molybdenum (Mo), Tungsten (W) are included in the 2D metasurface 20.

[00059] According to various non-limiting embodiments, the method 200 may include removing the mask layer 211 of the nanostructure 210 of the plurality of nanostructures 210, 220, 230, 240, as shown in FIG. 2A; and etching the (exposed) dielectric layer 213 of the

nanostructure 210 of the plurality of nanostructures 210, 220, 230, 240 (e.g. by reactive ion etching (RIE)) as shown in FIG. 2B. As shown in FIG. 2C, the etched dielectric layer 213a of the etched nanostructure 210a may consequently have a height less than its original height. Assuming that the plurality of nanostructures 210, 220, 230, 240 have substantially equal original heights as shown in FIG. 2A, the etched dielectric layer 213a of the etched nanostructure 210a of the plurality of nanostructure 210, 220, 230, 240 may have a height less than original heights of the remaining nanostructures 220, 230, 240, of the plurality of nanostructures 210, 220, 230, 240.

[00060] According to various non-limiting embodiments, a conductive atomic force microscopy (AFM) tip 260 may be used for removing the mask layer 211 of the nanostructure 210. That is, the AFM tip 260 may be used as an electrode to oxidize the mask layer 211 of the nanostructure 210. The same AFM tip 260 may be used for removing mask layers of the plurality of nanostructures 220, 230, and/or 240. A setpoint force of the AFM tip 260 may be in a range of nano-newton levels, particularly, in a range of 10 to 50 nano-newtons or specifically 10 to 20 nano-newtons. A bias in a range of 1.0 to 3.0 V, or specifically 2.0 to 2.5 V depending on the oxidation potential of the material used, may be applied to the AFM tip 260 to oxidize the mask layer 211 of the nanostructure 210 through the AFM tip 260 as one electrode. A solution 250 (e.g. an electrolyte **containing 1 mole of nickel sulfate ($NiSO_4$)** dissolved in 1 litre of solvent, typically water) may be subsequently used to dissolve the oxidized mask layer 211a of the nanostructure 210. In an example, the 2D metasurface 20 may be submerged into the solution 250 as shown in FIG. 2A.

[00061] According to various non-limiting embodiments, the method 200 may further include repeating the steps as shown in FIGS. 2A to 2D to form etched nanostructures 220a, 230a, and/or 240a (not shown in FIGS. 2A to 2D) based on the nanostructures 220, 230, 240, thereby forming the 3D metasurface. Heights of the etched nanostructures 220a, 230a, and/or 240a (not shown in FIGS. 2A to 2D) may vary from one another. According to various non-limiting embodiments, the method 200 may further include removing mask layers of unetched nanostructures of the plurality of nanostructures 210, 220, 230, 240 by a chemical wet etch to obtain the 3D metasurface 20a (step 30).

[00062] FIG. 2D shows a 3D metasurface 20a including the etched nanostructure 210a and the unetched nanostructure 220, 230, 240.

[00063] Another exemplary 3D metasurface 301 is shown in FIG. 3, the 3D metasurface 301 including the etched nanostructures 210a, 230a, 240a and the unetched nanostructure 220. Each of the etched nanostructures 210a, 230a, 240a has a different height, with a height of the etched nanostructure 230a less than a height of the etched nanostructure 210a, which is less than a height of the etched nanostructure 240a. The heights of the etched nanostructures 210a, 230a, 240a are less than a height of the unetched nanostructure 220 (i.e. the initial heights of the nanostructures 210, 220, 230, 240).

[00064] The AFM image 310 shows the nanostructures 230, 210, 240 (with Cr mask layers and TiO_2 dielectric layers) and the height profile 311 shows that the heights of the nanostructures 230, 210, 240 as extracted from the AFM image 310 are substantially equal. The AFM image 320 shows the nanostructures 230, 240 and the nanostructure 210 with its mask layer removed (i.e. the dielectric layer 213 of the nanostructure 210), and the height profile 321 shows that the height of the nanostructure 210 with its mask layer removed is 30 nm less than the heights of the nanostructures 230, 240 as extracted from the AFM image 320. In other words, the mask layer of the nanostructure 210 is about 30 nm thick. The AFM image 330 shows the (unetched) nanostructures 230, 240 and the etched nanostructure 210a, and the height profile 331 shows that the height of the etched nanostructure 210a is 100 nm less than the heights of the nanostructures 230, 240 as extracted from the AFM image 330. In other words, the dielectric layer of the nanostructure 210 is etched about 70 nm thick.

[00065] In one embodiment, the nanostructures 210, 220, 230, 240 may have a diameter of about 50 to 2000 nm and a height ranging from a few nanometers to a few micrometers, for example, about 200 nm. The nanostructures 210, 220, 230, 240 may be spaced apart by a spacing of 50 nm or greater. The minimum feature size (e.g. the smallest dimension or size of a pattern or structure that can be reliably created) by the present method may be of 10 nm.

[00066] FIG. 4 shows a 3D metasurface according to various embodiments of the present disclosure. The scale bar 41 represents 2 μm. The 3D metasurface shows "$a^{\star}$" pattern. The first set of (unetched) nanostructures 410 represents the background of the pattern with an initial height of 130 nm; the second set of (etched) nanostructures 420 represents the "$\star$" of the pattern with a height of 110 nm; and the third set of (unetched) nanostructures 430 represents the "a" of the pattern with a height of 100 nm. Each of the three sets of nanostructures 410, 420, 430, shows a respective color due to Mie resonance.

[00067] According to various non-limiting embodiments, a three-dimensional metasurface may include: a plurality of nanostructures including etched nanostructures and unetched nanostructures, wherein the etched nanostructures have varying heights, and wherein the etched nanostructures are in lateral alignment with the unetched nanostructures. In other words, the heights of the etched nanostructures may vary from one another. In some embodiments, the etched nanostructures are in lateral alignment with one another.

[00068] According to various non-limiting embodiments, the three-dimensional (3D) metasurface may be fabricated based on a two-dimensional (2D) metasurface by the methods 100, 200 as described hereinbefore. The 2D metasurface may include an array of subwavelength nanostructures in lateral alignment with one another due to the single lithography step used to form the array of subwavelength nanostructures. As used herein, the term "lateral" may refer to along surface/plane directions (e.g. x-y directions) of the 2D metasurface, for example, horizontal direction in FIGS. 2A to 2D. As used herein, the term "in lateral alignment with" may include "in complete lateral alignment with". "In complete lateral alignment with" may be interpreted as the alignment of the etched nanostructures being precisely (e.g. completely, entirely, absolutely, perfectly) aligned to the unetched nanostructures as references. Thus, the "complete lateral alignment" may mean that the etched nanostructures are precisely aligned, side by side, with the unetched nanostructures, ensuring accurate pattern transfer and minimizing (e.g. eliminating) any misalignment during fabrication of the etching. "In complete lateral alignment with" may refer to the alignment of the etched nanostructures and the unetched nanostructures with zero deviation.

[00069] According to various non-limiting embodiments, the unetched nanostructures may have a same height.

[00070] According to various non-limiting embodiments, each of the plurality of nanostructures including the etched nanostructures and the unetched nanostructures may include a dielectric layer (e.g. etched dielectric layers for the etched nanostructures and initial dielectric layers for the unetched nanostructures). The dielectric layer may be deposited on a silicon dioxide (SiO_2) substrate. The dielectric layer may include silicon, titanium dioxide, silicon nitride, or other group III-V or II-VI semiconductors.

[00071] According to various non-limiting embodiments, the same height of the unetched nanostructures may be an initial height of the initial dielectric layers of the unetched nanostructures.

[00072] In some embodiments, the etched nanostructures may include a first etched nanostructure and a second etched nanostructure, and a first height of the first etched nanostructure may be different from a second height of the second etched nanostructure. In some embodiments, the etched nanostructures may include a first set of etched nanostructures having a first same height and a second set of etched nanostructures having a second same height. The first set of etched nanostructures may have a first number of etched nanostructures that is same as or different from a second number of the second set of etched nanostructures. The first same height of the first set of etched nanostructures may be different from the second same height of the second set of etched nanostructures.

[00073] While the method described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[00074] While this specification contains many details, these should not be understood as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification or shown in the drawings in the context of separate implementations can also be combined. Conversely, various features that are described or shown in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination.

[00075] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

[00076] A number of implementations have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other implementations are within the scope of the following claims.

CLAIMS

1. A method for forming a three-dimensional metasurface, comprising:

forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface comprises a plurality of nanostructures including first to N-th nanostructures, wherein N is an integer greater than or equal to 2, each of the plurality of nanostructures comprising a mask layer and a dielectric layer disposed under the mask layer,

wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface comprises:

(i) removing an i-th mask layer of the i-th nanostructure of the plurality of nanostructures; and

(ii) etching an i-th dielectric layer of the i-th nanostructure of the plurality of nanostructure.

2. The method of claim 1, wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface further comprises:

removing a j-th mask layer of the j-th nanostructure of the plurality of nanostructures; and

etching a j-th dielectric layer of the j-th nanostructure of the plurality of nanostructure,

wherein an i-th height of the etched i-th nanostructure is different from a j-th height of the etched j-th nanostructure.

3. The method of claim 1 or claim 2, further comprising:

repeating the steps (i) and (ii) to form M etched nanostructures based on M nanostructures of the plurality of nanostructures, wherein M is an integer, equal to or greater than 2, and less than or equal to N.

4. The method of claim 3, wherein heights of the M etched nanostructures vary from one another.

5. The method of any of claims 1 to 4, wherein electrochemical oxidation is used for removing the respective mask layer of the plurality of nanostructures.

6. The method of claim 5, wherein a bias in a range of 1.0 to 3.0 V is applied to oxidize the respective mask layer of the plurality of nanostructures and a solution is subsequently used to dissolve the oxidized respective mask layer of the plurality of nanostructures.

7. The method of claim 5 or claim 6, wherein a conductive atomic force microscopy (AFM) tip is used for removing the respective mask layer of the plurality of nanostructures.

8. The method of claim 7 when dependent from claim 3 or claim 4, wherein the AFM tip is used for removing all mask layers of the M nanostructures of the plurality of nanostructures.

9. The method of claim 7 or claim 8, wherein a setpoint force of the AFM tip is in a range of nano-newton levels, particularly, in a range of 10 to 50 nano-newtons.

10. The method of any of claims 1 to 9, wherein the two-dimensional metasurface is fabricated by:

forming an initial mask layer on an initial dielectric layer;

etching the initial dielectric layer through the initial mask layer by lithography to form the 2-dimential metasurface.

11. The method of claim 10, wherein the method for forming the three-dimensional metasurface comprises one single lithography step being the lithography for forming the 2-dimential metasurface.

12. The method of claim 10 or claim 11, wherein the lithography includes reactive ion etch (RIE) process.

13. The method of any of claims 10 to 12, wherein the initial dielectric layer is deposited on a silicon dioxide (SiO_2) substrate.

14. The method of any of claims 10 to 13, wherein the initial mask layer comprises a metallic layer.

15. The method of any of claims 10 to 14, wherein the initial dielectric layer comprises silicon, titanium dioxide, silicon nitride, or other group III-V or II-VI semiconductors.

16. The method of any of claims 1 to 15, further comprising:

removing mask layers of unetched nanostructures of the plurality of nanostructures by a chemical wet etch to obtain the 3-dimentsion metasurface.

17. A method for forming a three-dimensional metasurface, comprising:

forming a three-dimensional metasurface based on a two-dimensional metasurface, wherein the two-dimensional metasurface comprises a plurality of nanostructures, each of the plurality of nanostructures comprising a dielectric layer,

wherein the forming a three-dimensional metasurface based on a two-dimensional metasurface further comprises:

forming an initial mask layer on the two-dimensional metasurface;

selectively removing a mask layer of at least one nanostructure of the plurality of nanostructures; and

etching a dielectric layer of the at least one nanostructure of the plurality of nanostructure.

18. A three-dimensional metasurface comprising:

a plurality of nanostructures comprising etched nanostructures and unetched nanostructures,

wherein the etched nanostructures have varying heights, and

wherein the etched nanostructures are in lateral alignment with the unetched nanostructures.

19. The three-dimensional metasurface of claim 18, wherein the unetched nanostructures have a same height.

20. The three-dimensional metasurface of claim 18 or claim 19, wherein the three-dimensional metasurface is chiral.