

A METHOD FOR FABRICATING AN OPTIC ELEMENT

TECHNICAL FIELD

[0001] The present disclosure generally relates to a method for fabricating an optic element, in particular, a method for fabricating metalenses using a top-down approach.

BACKGROUND

[0002] Compared to traditional bulky lenses, metalenses are lightweight, ultrathin, CMOS compatible, and integrable with optoelectronic components. They have attracted much attention for their unique properties. The current methods for fabricating metalenses commonly utilize the electron-beam lithography (EBL) followed by the dry etching method to form meta-atoms employed to control the phase delay of incidence light accurately. However, those approaches are not scalable for mass production due to the limitation of the EBL, which hinders the commercialization progress of the metalens technology.

[0003] Therefore, there exists a need to provide high throughput and large area fabrication processes to make flat optics and metalenses in the industry, particularly in light detection and ranging (LiDAR), Augmented Reality (AR) / Virtual Reality (VR), smartphone camera modules, etc.

SUMMARY

[0004] According to a first aspect of the present disclosure, a method for fabricating an optic element is provided. The method includes: fabricating a first mold having a pattern of the optic element; fabricating a second mold by using the first mold, the second mold have an opposite pattern to the pattern of the optic element; nanoimprinting the second mold into a resin layer on a base of the optic element so as to form the pattern of the optic element on the resin layer; and etching the base of the optic element to form the optic element, wherein the base of the optic element is fabricated by depositing a metallic layer on a film structure, the film structure deposited on a substrate, and the resin layer is applied on the metallic layer of the base of the optic element.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is a flowchart showing a method for fabricating an optic element according to various embodiments of the present disclosure.

[0006] FIG. 2 is a block diagram depicting a method for fabricating an optic element according to various embodiments of the present disclosure.

[0007] FIG. 3 shows optical microscopy (top views) and scanning electron microscopy (SEM) (bottom views) images of the optic element fabricated by the method of FIG. 2.

[0008] FIG. 4 are graphs showing phase shift and transmission of an optic element according to various embodiments of the present disclosure.

[0009] FIG. 5 is a graph showing simulated point spread function (PSF) of an optic element at a focal plane thereof, according to various embodiments of the present disclosure.

[00010] FIG. 6 shows optical characterization of an optic element according to various embodiments of the present disclosure.

[00011] FIG. 7 shows optical characterization of an optic element 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] The term “mold” may be used herein to mean a tool or template or stamp used in a fabrication process (i.e. a molding process) to shape or form materials corresponding to a desired pattern or model specification of a final product. A mold may typically have a cavity (e.g. gap) that defines the external shape of the product and a core that defines internal features of the product. A mold may be used repeatedly for a large number of production cycles.

[00017] The term “optic element” may be used herein to mean any component or device that interacts with light for the purpose of manipulating or controlling its properties. Optic elements may be used in various fields, including optics, photonics, imaging, and telecommunications. An optic element may include a metalens, and/or a component of the metalens.

[00018] The term “metalens” may be used herein to mean a type of lens that uses nanoscale structures, often made of metamaterials or nanostructures, to control the phase and amplitude of light at the subwavelength scale. Unlike traditional lenses, which are made of bulk materials and rely on curved surfaces to refract light, metalenses may utilize engineered patterns at the nanoscale to achieve specific optical properties. Metalenses have gained significant attention in the field of optics and photonics due to their potential for compact size, lightweight design, and the ability to overcome some limitations of conventional lenses.

[00019] As used herein, the term “pattern” may refer to the specific arrangement and design of nanoscale structures (e.g. concentric circles, gratings, or other geometric configurations) on the surface of an optic element (e.g. a metalens). Metalenses may utilize these patterns to control the phase and amplitude of light, allowing for precise manipulation of light waves at the subwavelength scale. The patterns on a metalens may play a crucial role in determining its optical properties and performance.

[00020] As used herein, the term “opposite pattern” may refer to a reversal or inversion of a given pattern. This may involve inverting the elements of the pattern to create a reversed version. In the context of various embodiments, the pattern and the opposite pattern may refer to two patterns supplementary to each other in a manner that a profile (e.g. outline,

configuration) of the pattern conforms (e.g. match) to a profile (e.g. outline, configuration) of the opposite pattern in an inverted way. For example, in the context of a flat optic element, a protrusion in the pattern corresponds to a recess in the opposite pattern such that the protrusion fits closely in the recess.

[00021] As used herein, the term “nanoimprinting” may refer to a nanofabrication technique used to create patterns and structures at the nanoscale by replicating nanoscale features from a mold onto a target material. Ultraviolet (UV) nanoimprint lithography may involve using a transparent mold with a nanoscale relief pattern. The mold may be brought into contact with a UV-curable resin on a substrate. The resin may be then cured using UV light, creating a replica of the mold pattern on the substrate.

[00022] As used herein, the term “resin” may broadly refer to a class of synthetic or naturally occurring compounds that are typically viscous and may harden into a solid or semi-solid state. A resin may include a polymer resin, a thermosetting resin, a thermoplastic resin, a UV-curable resin and the like. A UV-curable resin may cure or harden when exposed to UV light. In the context of nanoimprinting, resins may be used as a material for the imprinting process.

[00023] As used herein, the term “resist” may refer to, in the context of lithography, a light-sensitive material that is used as a coating on a substrate to create patterns. The resist may undergo chemical or physical changes when exposed to light, and this property may be utilized in processes like photolithography. A resin may include a resist for utilization in photolithograph.

[00024] As used herein, the term “soft material” may refer to materials that may be easily deformed by thermal stresses or thermal fluctuations at about room temperature, including liquids, polymers, foams, gels, colloids, granular materials, and the like. Particularly, the soft material may include a UV-curable resin (e.g. polymer stamp materials including GMN-PS90 (foil) by OpTool ApS, Sweden), a photo-curable resin or a thermal-curable resin. GMN-PS90 may be a promising polymer material for nanoimprint lithography, offering good performance in terms of surface morphology and high-resolution pattern transfer.

[00025] According to various non-limiting embodiments, a large-area high-resolution (<100 nm) fabrication process using a top-down approach is presented including nanoimprinting lithography (NIL) followed by dry etching, which may make flat optical components of various materials. The top-down fabrication may allow for precise control over the size, shape, and placement of features and be generally scalable to larger production volumes. Further, top-down processes may be often compatible with existing semiconductor manufacturing techniques and thus this compatibility may make it easier to integrate new technologies into

established manufacturing environments, reducing costs and time. Techniques like photolithography, etching, and other high-throughput methods may allow for the simultaneous fabrication of multiple devices on a single substrate. This present approach may offer a cost-effective solution for mass production of flat optics to address the industry's needs. The present method may involve a combination of lithography, imprinting, and (dry) etching steps to create well-defined nanopillars on the silicon wafer substrate. The detailed control and sequential nature of the steps contribute to the precision and reproducibility of the fabricated structures.

[00026] Various embodiments of what is described here seek to provide a method for fabricating an optic element (e.g. a metalens), for example, the proposed method may include fabrication of a master mold via electron beam lithography (EBL) and dry etching. The proposed method may further include fabrication of a soft mold by using the master mold, pattern transferred from the master mold to the soft mold in an inverted way. The proposed method may also include resin (e.g. a resist) patterning via nanoimprinting by the soft mold, followed by dry etching into a metallic layer and a thin film (e.g. dielectric thin film) along with a substrate beneath the resin (e.g. the resist) to form the optic element (e.g. the metalens). Parameters including power, gas flow, gas ratio, interval and time for dry etching may be further determined to achieve the present optic element. The present method may fabricate a first mold (e.g. a master mold) and a second mold (e.g. a soft mold), and the second mold (e.g. the soft mold) may be repeated used to obtain optic elements (e.g. metalenses) by the process as described herein. Hence, the present method may be scalable and versatile for high-volume manufacturing of flat optical components made of various materials such as metal, dielectrics, semiconductors, and phase change materials. The present method advantageously and efficiently provides an optic element (e.g. a metalens) with high aspect ratio. Furthermore, the present method may advantageously and efficiently fabricate flat optics at a wafer level via cost-effective nanoimprinting process, and typical dry etching process, which is scalable for mass production of different metalenses consisting of various materials. That is, a single device may include multiple metalenses, each of which is made of a different material catered for a different function (e.g. a different phase shift). It may address the industry needs for multifunctional flat optics for applications in light detection and ranging (LiDAR), Augmented Reality (AR) / Virtual Reality (VR), smartphone camera modules, optical imaging, miniaturized optical microscope, microspectrometer, etc.

[00027] In various embodiments, the soft mold may be fabricated by an ultraviolet (UV) curable soft material (e.g. polymer stamp materials including GMN-PS90 (foil) by OpTool ApS, Sweden) and the soft mold may be nanoimprinted into a high-performance resin layer

(e.g. mr-NIL212FC (Microresist Technology)) on a base of the optic element so as to form the pattern of the optic element on the resin layer. Compatibility may be considered when selecting the soft material for the soft mold and the resin material for the resin layer in a manner that they are compatible to facilitate smooth demolding between the soft mold and the resin layer (e.g. thereby achieving substantially vertical walls of the patterned resin layer, i.e. high aspect ratio).

[00028] According to various non-limiting embodiments, the soft mold may be nanoimprinted into a high-performance resin layer (e.g. mr-NIL212FC (Microresist Technology)) on a base of the optic element and a metallic layer (e.g. chromium) may be deposited on a film structure of the base of the optic element (e.g. high refractive index dielectrics, semiconductors, phase change materials, etc.). An etching selectivity equal to or greater than 6 to 1 may be achieved between the resin layer and the metallic layer. An etching selectivity may be a ratio of an etch rate of an etch mask (e.g. the metallic layer) and an etch rate of a material of interest (e.g. the film structure). The resin layer may be sufficiently thick (e.g. 100 nm) for etching through the metallic layer (e.g. 10 nm), which in turn serves a hard mask for etching the film structure (e.g. amorphous silicon, 550 nm) along with a substrate for forming the high-efficiency optic element with high aspect ratio equal to or greater than 5 to 1. The present method provides valuable insights into the dry etching behavior and suitability of mr-NIL212FC in the fabrication process involving metals like chromium. An etching selectivity equal to or greater than 6 to 1 may be achieved between the metallic layer and the film structure along with the substrate beneath the metallic layer.

[00029] The following examples pertain to various aspects of the present disclosure.

[00030] Example 1 is a method for fabricating an optic element, including: fabricating a first mold having a pattern of the optic element; fabricating a second mold by using the first mold, the second mold have an opposite pattern to the pattern of the optic element; nanoimprinting the second mold into a resin layer on a base of the optic element so as to form the pattern of the optic element on the resin layer; and etching the base of the optic element to form the optic element, wherein the base of the optic element is fabricated by depositing a metallic layer on a film structure, the film structure deposited on a substrate, and the resin layer is applied on the metallic layer of the base of the optic element.

[00031] In Example 2, the subject matter of Example 1 may optionally include that fabricating a first mold having a pattern of the optic element includes: applying an etch mask layer on a wafer; patterning the etch mask layer by electron-beam lithography to form the pattern of the optic element on the etch mask layer; and etching the wafer through the patterned

etch mask layer by deep reactive-ion etching (DRIE) to form the pattern of the optic element in the wafer as the first mold.

[00032] In Example 3, the subject matter of Example 2 may optionally include that the etch mask layer includes hydrogen silsesquioxane (HSQ), a NEB-22 resist by Sumitomo Chemical, an AR-N 7520 resist by ALLRESIST GmbH, a maN resist by micro resist technology GmbH or a ZEP resist by Zeon Corporation.

[00033] In Example 4, the subject matter of any of Examples 1 to 3 may optionally include that fabricating a second mold by using the first mold including: dropping cast a soft material onto the first mold; and applying ultraviolet (UV) nanoimprinting process to transfer the opposite pattern to the soft material to obtain the second mold.

[00034] In Example 5, the subject matter of Example 4 may optionally include that the soft material includes a UV-curable resin, a photo-curable resin or a thermal-curable resin.

[00035] In Example 6, the subject matter of Example 4 or Example 5 may optionally include applying pressure on the drop-casted soft material using a stamping substrate with an adhesion layer thereon being in contact with the drop-casted soft material.

[00036] In Example 7, the subject matter of any of Examples 1 to 6 may optionally include coating the first mold using a self-assembled monolayer (SAM) prior to fabricating the second mold by using the first mold.

[00037] In Example 8, the subject matter of any of Examples 1 to 7 may optionally include that the film structure of the base of the optic element includes a film of silicon (Si), amorphous silicon (a-Si), silicon dioxide (SiO₂), silicon nitride (Si₃N₄), titanium dioxide (TiO₂), germanium-antimony-tellurium (GeSbTe), hafnium dioxide (HfO₂), and a semiconductor including indium phosphide (InP) or gallium arsenide (GaAs).

[00038] In Example 9, the subject matter of any of Examples 1 to 8 may optionally include that the metallic layer includes a chromium layer.

[00039] In Example 10, the subject matter of any of Examples 1 to 9 may optionally include that the resin layer is spin-coated onto the metallic layer of the base of the optic element.

[00040] In Example 11, the subject matter of any of Examples 1 to 10 may optionally include that the nanoimprinted resin layer is stripped by around tens of nanometers to remove a residual of the nanoimprinted resin layer so as to expose the metallic layer.

[00041] In Example 12, the subject matter of any of Examples 1 to 11 may optionally include that etching the base of the optic element to form the pattern of the optic element includes: etching the metallic layer in a gas mixture of chlorine gas and oxygen gas; and dry-

etching the film structure and the substrate using the etched metallic layer as a hard mask in a gas mixture including sulfur hexafluoride (SF₆), octafluorocyclobutane (C₄F₈) and argon (Ar).

[00042] In Example 13, the subject matter of Example 8 may optionally include removing the etched metallic layer by an etchant solution to obtain the optic element.

[00043] In Example 14, the subject matter of any of Examples 1 to 13 may optionally include repeating the steps (iii) and (iv) to form a plurality of the optic elements having the pattern.

[00044] In Example 15, the subject matter of any of Examples 2 to 14 may optionally include that the wafer includes silicon (Si) deposited on a silicon dioxide (SiO₂) substrate.

[00045] In Example 16, the subject matter of any of Examples 4 to 15 may optionally include that the soft material includes a polymer stamp material.

[00046] In Example 17, the subject matter of any of Examples 1 to 16 may optionally include that the resin layer includes a photo-curable resin, the photo-curable resin includes 2-methoxy-1-methylethyl acetate, ethoxylated bisphenol A diacrylate and 2-(2-((oxo(phenyl)acetyl)oxy)ethoxy)ethyl oxo(phenyl)acetate.

[00047] In Example 18, the subject matter of any of Examples 1 to 17 may optionally include that an etching selectivity of the resin layer to the metallic layer is equal to or greater than 5 to 1.

[00048] In Example 19, the subject matter of any of Examples 1 to 18 may optionally include that the optic element includes nanopillars having an aspect ratio of equal to or greater than 5 to 1.

[00049] In Example 20, the subject matter of any of Examples 1 to 19 may optionally include that an etching selectivity of the metallic layer to the film structure is equal to or greater than 5 to 1.

[00050] FIG. 1 is a flowchart showing a method 100 for fabricating an optic element (e.g. a metalens) according to various embodiments of the present disclosure. The method 100 may include: at step 102, (i) fabricating a first mold having a pattern of the optic element; at step 104, (ii) fabricating a second mold by using the first mold, the second molding have an opposite pattern to the pattern of the optic element; at step 106, (iii) nanoimprinting the second mold into a resin layer on a base of the optic element so as to form the optic element on the resin layer; and at step 108, (iv) etching the base of the optic element to form the pattern of the optic element. The base of the optic element may be fabricated by depositing a metallic layer on a film structure, the film structure deposited on a substrate, and the resin layer may be applied on the metallic layer of the base of the optic element.

[00051] According to various non-limiting embodiments, the present method 100 may provide a massive fabrication process using a top-down approach, i.e., nanoimprint lithography (NIL) in combination with a dry etching method. The first mold may be referred as a master mold. In some embodiments, the first mold may be fabricated by: applying an etch mask layer on a wafer; patterning the etch mask layer by electron-beam lithography to form the pattern of the optic element on the etch mask layer; and etching the wafer through the patterned etch mask layer by deep reactive-ion etching (DRIE) to form the pattern of the optic element in the wafer as the first mold. It should be appreciated that the method of fabricating the first mold is not limited to the above, other known methods for fabricating the first mold are also included in the present method 100. The wafer may include a silicon wafer (e.g. silicon on silicon dioxide) typically made from a single crystal or polycrystalline silicon. The diameters of the wafer may include 100 mm (4 inches), 150 mm (6 inches), 200 mm (8 inches), 300 mm (12 inches) and any available diameter of wafers, and the thickness of the wafer may include, but not be limited to, a range from around 200 to 1000 μm .

[00052] According to various non-limiting embodiments, the etch mask layer may include a resist selected from hydrogen silsesquioxane (HSQ), a NEB-22 resist by Sumitomo Chemical, an AR-N 7520 resist by ALLRESIST GmbH, a maN resist by micro resist technology GmbH and a ZEP resist by Zeon Corporation.

[00053] According to various non-limiting embodiments, the method may further include coating the first mold using a self-assembled monolayer (SAM) prior to fabricating the second mold by using the first mold. This may avoid or prevent material from sticking onto the first mold.

[00054] According to various non-limiting embodiments, the master mold may be used to transfer the pattern of the optic element onto the second mold through ultraviolet (UV) nanoimprinting lithography. The second mold may include a soft mold. In some embodiments, the second mold may be fabricated by dropping cast a soft material onto the first mold; and applying UV nanoimprinting process to transfer the opposite pattern to the soft material to obtain the second mold. In other words, the soft material may be disposed on the first mold in a manner that the soft material fills (e.g. recesses of) the first mold to form an opposite pattern of the first mold, i.e., the opposite pattern of the optic element. Accordingly, the second mold formed by the soft material may have a profile (e.g. outline, configuration) matching a profile (e.g. outline, configuration) of the first mold in an inverted way. Similarly as the method of fabricating the first mold, it should be appreciated that the method of fabricating the second

mold is not limited to the above, other known methods for fabricating the second mold by using the first mold are also included in the present method 100.

[00055] According to various non-limiting embodiments, the method 100 may further include applying pressure on the drop-casted soft material using a stamping substrate with an adhesion layer thereon being in contact with the drop-casted soft material. The soft material may be pressed by the stamping substrate to substantially or fully fill the first mold so as to form the second mold having the opposite pattern to the pattern of the optic element.

[00056] According to various non-limiting embodiments, the soft mold may be used to nanoimprint onto the resin (e.g. mr-NIL212FC) layer coated (e.g. spin-coated) on the base of the optic element. In other words, the resin may fill the soft mold such that the resin forms the pattern of the optic element by filling up the opposite pattern of the soft mold. The nanoimprinted resin layer may be stripped by around tens of nanometers to remove a residual of the nanoimprinted resin layer so as to expose the metallic layer. Mr-NIL212FC may have good performance as an etch mask for chromium, with precise sidewall accuracy and excellent lateral accuracy over a large area.

[00057] After the nanoimprinting, dry etching may be employed to etch the base of the optic element to form the optic element. In some embodiments, etching the base of the optic element to form the optic element may include: etching the metallic layer in a gas mixture (e.g. a gas mixture of chlorine gas and oxygen gas); and dry etching the film structure and the substrate using the etched metallic layer as a hard mask in a gas mixture (e.g. a gas mixture including sulfur hexafluoride (SF_6), octafluorocyclobutane (C_4F_8) and argon (Ar)). Etching the metallic layer may use the patterned resin layer as the etch mask and accordingly, the resin layer may be a resist layer. In some embodiments, the method 100 may include removing the etched metallic layer by an etchant solution to obtain the optic element (e.g. a metalens).

[00058] According to various non-limiting embodiments, the resin layer may include a photo-curable resin, and the photo-curable resin may include 2-methoxy-1-methylethyl acetate, ethoxylated bisphenol A diacrylate, and 2-(2-((oxo(phenyl)acetyl)oxy)thoxy)ethyl oxo(phenyl)acetate.

[00059] According to various non-limiting embodiments, the film structure of the base of the optic element may include a film of silicon (Si), amorphous silicon (a-Si), silicon dioxide (SiO_2), silicon nitride (Si_3N_4), titanium dioxide (TiO_2), germanium-antimony-tellurium (GeSbTe), hafnium dioxide (HfO_2), and a semiconductor including indium phosphide (InP) or gallium arsenide (GaAs). The substrate of the film structure may include quartz.

[00060] 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 method 100.

[00061] According to various non-limiting embodiments, the method 100 may include repeating the steps (iii) and (iv) to form a plurality of the optic elements having the pattern. Alternatively or additionally, a plurality of optic elements may be simultaneously fabricated on a same base including a metallic layer and a film structure deposited on a substrate using a plurality of second molds, each of the second molds may include a different pattern according to a different requirement.

[00062] According to various non-limiting embodiments, an etching selectivity of the resin layer to the metallic layer may be equal to or greater than 5 to 1, or 6 to 1, or between 5 to 1 and 6 to 1. The optic element may include nanopillars having an aspect ratio of equal to or greater than 5 to 1, or 6 to 1, or between 5 to 1 and 6 to 1. An etching selectivity of the metallic layer to the film structure may be equal to or greater than 5 to 1, or 6 to 1, or between 5 to 1 and 6 to 1.

[00063] FIG. 2 is a block diagram depicting a method 200 for fabricating a flat optic element (e.g. a metalens) according to various embodiments of the present disclosure.

[00064] FIG. 3 shows images of optical microscopy (top views) and scanning electron microscopy (SEM) (bottom views) of the optic element fabricated by the method 200 of FIG. 2.

[00065] The pattern shown in FIGS. 2 and 3 may represent a metalens with a working wavelength (λ) of 940 nm, a numerical aperture (NA) of 0.5, and a lens diameter (D) of 500 μm .

[00066] 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*.

[00067] According to various non-limiting embodiments, the method 200 may include Step 1, fabricating a master mold 210; Step 2, fabricating a soft mold by using the first mold 220; Step 3, fabricating a hard mask 230; Step 4, fabricating a resist mask 240; and Step 5, fabricating a metalens 250. The details of the above five steps will be described as follows.

[00068] Step 1, fabricating a master mold 210.

[00069] A flat lens pattern may be obtained by using the electron-beam lithography (EBL) (Elionix ELS-7000) with hydrogen silsesquioxane (HSQ) as an etch mask for pattern transfer from the HSQ to a wafer (e.g. silicon on silicon dioxide). The HSQ may be used to obtain the master mold having nanopillars with high aspect ratio. The nanopillars may have varying diameters.

[00070] At step 212, HSQ solution may be spin-coated on a (silicon) wafer at a speed of 1500 rpm for 60 s, giving rise to a thickness of about 160 nm. The thickness of HSQ may be more than 100nm to provide the intended purpose. A designed layout (i.e. the pattern) of the flat optic element may be patterned on the HSQ by e-beam at an acceleration voltage of 100 kV and a dose of 7600 $\mu\text{C}/\text{cm}^2$. The HSQ may be developed in salty developer (KOH 1%, NaCl 4%, deionized (DI) water 95%) for 60 s and rinsed with DI for 60 s to form the etch mask. Experimental parameters are provided as a reference for the present method 200 and should not be used to limit the present method 200. It should be appreciated that known methods with different experimental parameters are included in the method 200.

[00071] At step 214, the (silicon) master mold with the designed flat lens pattern may be produced using the deep reactive-ion etching (DRIE) process (Oxford Plasmalab 100) through the HSQ etch mask on the (silicon) wafer. The DRIE process with a controlled mixture of HBr (50 sccm) and O₂ (3 sccm) gas, pressure of 5mT, RIE power of 150W, ICP of power 800W, for 90 s may be used to attain smooth and controllable sidewalls of the resultant flat lens pattern. The etched thickness of Si after 90s may be around 200nm, that is, nanopillars of the master mold has a height of about 200nm. The remaining HSQ layer (i.e. the remaining HSQ etch mask) may be removed chemically by dipping samples in buffered hydrofluoric (HF) solution for 2 minutes. The master mold may be formed from the (silicon) wafer with the nanopillars having a high aspect ratio (e.g. greater than 2 to 1).

[00072] Step 2, fabricating a soft mold by using the first mold 220.

[00073] The pattern from the (silicon) master mold may be transferred to the soft mold in an inverted way, which may be used repeatedly for the subsequent nanoimprint lithography (NIL) process.

[00074] At step 222, the (silicon) master mold composed of the (silicon) nanopillars as fabricated in Step 1 may be employed as the master mold. A self-assembled monolayer (SAM) coating process (not shown) may be applied to avoid material sticking onto the master mold before the soft mold preparation process. The SAM may have a thickness of less than 1nm. A UV-curable resin (e.g. polymer stamp materials including GMN-PS90 (foil) by OpTool ApS,

Sweden) may be employed as the soft material and drop cast onto the master mold. The UV-curable resin may fill the (silicon) master mold so as to form an opposite pattern to the pattern of the master mold. In other words, the UV-curable resin may fill gaps between the nanopillars of the master mold so as to form an opposite pattern to the pattern of the master mold. The UV-curable resin may have a thickness of greater than 1 μm .

[00075] A quartz substrate (not shown) (e.g. with a thickness of 0.7 mm) may be cleaned with acetone, isopropyl alcohol (IPA), and DI water, followed by O₂ plasma treating. Then, a resist (e.g. mr-aps 1 from Microresist technology) may be spin-coated onto the quartz substrate with a spin speed of 3000 rpm for 40 s to obtain a thickness of several μm . The quartz substrate may be put on the master mold with the resist coated surface contacting with the drop-casted GMN, thereby applying a pressure on the drop-casted GMN. In other words, the soft material may be sandwiched by the quartz substrate and the master mold so as to form the soft mold by the pressure exerted therebetween.

[00076] At step 224, the soft mold may be achieved using UV nanoimprinting process. The UV exposure time may be 600 s, and the operating pressure may be 0 bar and 600 s. Manually demolding may be employed to obtain the soft mold. The soft mold may have the opposite pattern to the pattern of the optic element (i.e. the pattern of the master mold).

[00077] Step 3, fabricating a hard mask 230.

[00078] A hard mask may be fabricated for forming the optic element by photolithography.

[00079] At step 232, the amorphous silicon ($\alpha\text{-Si}$) (e.g. with a thickness 550 nm) may be deposited on a quartz substrate (i.e. a crystalline silicon dioxide) by Plasma Enhanced Chemical Vapor Deposition (PECVD). The amorphous silicon (e.g. a glass) may be utilized for its optical (e.g. with a wider bandgap) and electronic (e.g. being a semiconductor) properties compared to crystalline silicon. A layer of chromium (Cr) (e.g. with a thickness of 20 nm) may be deposited on the amorphous silicon via electron beam deposition. The Cr layer may be employed as a hard mask for the subsequent amorphous silicon etching. It should be appreciated the hard mask is not limited to chromium, at least other Group 6 (VIb) metal elements including molybdenum (Mo), Tungsten (W) are included in the method 200. The structure including the hard mask, the amorphous silicon and the quartz substrate may be referred as a base of the optic element.

[00080] At step 234, the resin (e.g. mr-NIL212FC (Microresist Technology)) may be spin-coated onto the Cr/ $\alpha\text{-Si}$ /quartz substrate with a speed of 2500 rpm for 30 s, which results in about 100 nm thickness of the resin layer. It should be appreciated that the resin is not limited

to the mr-NIL212FC, but include any (organic) photo-curable NIL resist with suitable etching selectivity for the hard mask.

[00081] Step 4, fabricating a resist mask 240 by nanoimprinting the resin layer.

[00082] An etching selectivity of the resin mask to the hard mask may be equal to or greater than 5 to 1. The resulted optic element may include nanopillars having an aspect ratio of equal to or greater than 5 to 1.

[00083] At step 242, the fabricated soft mold may be put on the surface of resin/Cr/a-Si/quartz and followed by UV nanoimprinting process. The nanoimprinting pressure, UV exposure time, and temperature may be 0 bar, 600 s, and 25 °C, respectively.

[00084] At step 244, manual demolding may be applied to obtain the pattern of the optic element on the resin layer.

[00085] Step 5, fabricating a metalens 250.

[00086] At step 252, the residual resin layer may be stripped by around 20 nm (e.g. ultrathin residual resin layer) to expose the Cr layer with a gas of O₂ (50 sccm), pressure of 0.1 mT, RIE power of 100 W, chamber temperature of 10°C, for 15 s in Oxford Plasmalab System. The Cr layer may be then etched within Oxford OIPT Plasmalab System with a mixture of gas Cl₂ (19 sccm) and O₂ (2 sccm), pressure of 10mT, RIE power of 50 W, ICP power of 600 W, and chamber temperature of 6°C for 100 s. The flat lens may be transferred into the amorphous silicon by dry etching with Cr as a hard mask. The 550-nm amorphous silicon nanopillars may be fabricated in Advance Dielectric Etch Deep RIE (SPTS) with a mixture of gas of SF₆ (36 sccm), C₄F₈ (44 sccm) and Ar (20 sccm), pressure of 19mT, Platen power of 45 W, Coil power of 825 W, chamber temperature of 20°C for 100 s.

[00087] At step 254, the metalens (i.e. the optic element) may be cleaned by removing the residual Cr layer in Cr etchant solution for 120 s.

[00088] According to various non-limiting embodiments, the soft mold obtained at step 224 may be repeated applied to obtain a plurality of optic elements. That is, Steps 3, 4 and 5 as shown in FIG. 2 may be repeated to obtain a plurality of optic elements (i.e. metalenses). In some embodiments, a plurality of soft molds may be fabricated with varying parameters (e.g. periods, diameters of nanopillars) and the plurality of soft molds may be applied simultaneously to obtain metalenses with the varying parameters and/or periods.

[00089] 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.

[00090] Now referring to FIG. 3, the top views of the Steps 1, 2, and 5 are from optical microscopy and the bottom views of the Steps 1, 2 and 5 are from scanning electron microscopy (SEM). It can be seen in the bottom view of Step 1, the master mold having nanopillars with different diameters is shown to have high aspect ratio (e.g. vertical sidewalls); in the bottom view of Step 2, the soft mold is shown to have an opposite pattern to the pattern of the master mold as shown in the bottom view of Step 1, that is, the holes as shown in the bottom view of Step 2 correspond to the nanopillars as shown in the bottom view of Step 1; in the bottom view of Step 5, the optic element (e.g. the metalens) is shown having the pattern corresponding to the master mold as shown in the views of Step 1.

[00091] According to various non-limiting embodiments, the pattern of the optic element may be designed using Rigorous coupled-wave analysis (RCWA). The optic element (e.g. a metalens) may be designed to impart a phase shift to incident light and a phase distribution may follow the shape of a hyperbola. The hyperbolic phase profile may be discretized and mapped using the nanopillars of the optic element (e.g. the metalens).

[00092] FIG. 4 are graphs showing phase shift 402 and transmission 404 of an optic element, a nanopillar 406 of which is shown in the inset of FIG. 4, e.g. a unit cell, according to various embodiments of the present disclosure. The optic element may be fabricated by the methods 100, 200 as described hereinbefore.

[00093] According to various non-limiting embodiments, the optic element may be made of (silicon) nanopillars on a substrate (e.g. a glass). The nanopillar 406 of the optic element may be periodically repeated along the surface of the substrate in two orthogonal directions to form the optic element (e.g. a metalens including a plurality of unit cells). The nanopillar 406 may have a height of 550 nm and a period of 450 nm, and the diameter of the nanopillar 406 may vary from 150 to 300 nm. The nanopillar 406 may introduce phase shift in the incident wave depending on the diameter of the nanopillar 406. Phase shift and transmission of the optic element are shown as functions of the diameter of the nanopillar 406. Accordingly, the diameter of the nanopillar 406 may be determined so as to meet its phase shift and transmission requirements.

[00094] FIG. 5 is a graph showing simulated point spread function (PSF) of the optic element fabricated by the methods 100, 200 as described above at a focal plane thereof, according to various embodiments of the present disclosure. The optic element may have a

total lens diameter of 500 (200) μm , focusing at 433 (173) μm , NA of about 0.5. Resulting focusing is simulated using Fourier transform calculations with point spread function (PSF). The focusing efficiency is 82.1%.

[00095] FIG. 6 shows optical characterization of an optic element according to various embodiments of the present disclosure. The optic element may be fabricated by the methods 100, 200 as described above. FIG. 6 depicts the intensity distribution of the focal spot at the y-z plane (left inset) and x-y plane (right inset), where z is beam propagation direction. The graph 602 shows the intensity amplitude at a wavelength of 940 nm.

[00096] FIG. 7 shows optical characterization of metalenses formed by an optic element according to various embodiments of the present disclosure. The optic element may be fabricated by the methods 100, 200 as described above. FIG. 7 depicts focusing efficiency of 22.7% and the back focal plane imaging (inset) shows measured NA of the optic element as 0.5.

[00097] Table I compares the performance between the design and the measurement of the optic element (e.g. the metalens). It can be observed that the deviation of the focal length is around 20 μm , approximately 4.6% of the design parameter, which is within the acceptable range. The measured full width at half maximum (FWHM) of the focus matches numerically calculated FWHM within measurements errors. The measured focusing efficiency was about 22.7%, which may be due to the imperfections of fabrication (e.g. fabrication errors/defects), including the sidewall profile and diameter of nanopillars. This can be improved by improving the sidewall angle to be $> 85^\circ$ and the accuracy of the fabrication (e.g. etching nearly 90° sidewall profile and minimizing size variation of the nanopillars (e.g. within 10nm in terms of the nanopillar diameter)).

[00098] TABLE I. Comparison the technical specification between design and characterization of the metalenses

	Focal length (μm)	FWHM of the focal spot (nm)	Focusing efficiency (%)
Design	433	940	82.1
Measurement	452 $\pm$ 5	940 $\pm$ 32	22.7

[00099] 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.

[000100] 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.

[000101] 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 fabricating an optic element, the method comprising:
 - (i) fabricating a first mold having a pattern of the optic element;
 - (ii) fabricating a second mold by using the first mold, the second mold have an opposite pattern to the pattern of the optic element;
 - (iii) nanoimprinting the second mold into a resin layer on a base of the optic element so as to form the pattern of the optic element on the resin layer; and
 - (iv) etching the base of the optic element to form the optic element, wherein the base of the optic element is fabricated by depositing a metallic layer on a film structure, the film structure deposited on a substrate, and the resin layer is applied on the metallic layer of the base of the optic element.
2. The method of claim 1, wherein fabricating a first mold having a pattern of the optic element comprises:
 - applying an etch mask layer on a wafer;
 - patterning the etch mask layer by electron-beam lithography to form the pattern of the optic element on the etch mask layer; and
 - etching the wafer through the patterned etch mask layer by deep reactive-ion etching (DRIE) to form the pattern of the optic element in the wafer as the first mold.
3. The method of claim 2, wherein the etch mask layer comprises hydrogen silsesquioxane (HSQ), a NEB-22 resist by Sumitomo Chemical, an AR-N 7520 resist by ALLRESIST GmbH, a maN resist by micro resist technology GmbH or a ZEP resist by Zeon Corporation.
4. The method of claim 1, wherein fabricating a second mold by using the first mold comprising:
 - dropping cast a soft material onto the first mold; and
 - applying ultraviolet (UV) nanoimprinting process to transfer the opposite pattern to the soft material to obtain the second mold.
5. The method of claim 4, wherein the soft material comprises a UV-curable resin, a photo-curable resin or a thermal-curable resin.

6. The method of claim 4, further comprising:
applying pressure on the drop-casted soft material using a stamping substrate with an adhesion layer thereon being in contact with the drop-casted soft material.
7. The method of claim 1, further comprising:
coating the first mold using a self-assembled monolayer (SAM) prior to fabricating the second mold by using the first mold.
8. The method of claim 1, wherein the film structure of the base of the optic element comprises a film of silicon (Si), amorphous silicon (a-Si), silicon dioxide (SiO₂), silicon nitride (Si₃N₄), titanium dioxide (TiO₂), germanium-antimony-tellurium (GeSbTe), hafnium dioxide (HfO₂), and a semiconductor including indium phosphide (InP) or gallium arsenide (GaAs).
9. The method of claim 1, wherein the metallic layer comprises a chromium layer.
10. The method of claim 1, wherein the resin layer is spin-coated onto the metallic layer of the base of the optic element.
11. The method of claim 1, wherein the nanoimprinted resin layer is stripped by around tens of nanometers to remove a residual of the nanoimprinted resin layer so as to expose the metallic layer.
12. The method of claim 1, wherein etching the base of the optic element to form the pattern of the optic element comprises:
etching the metallic layer in a gas mixture of chlorine gas and oxygen gas; and
dry-etching the film structure and the substrate using the etched metallic layer as a hard mask in a gas mixture comprising sulfur hexafluoride (SF₆), octafluorocyclobutane (C₄F₈) and argon (Ar).
13. The method of claim 8, further comprising:

removing the etched metallic layer by an etchant solution to obtain the optic element.

14. The method of claim 1, further comprising:
repeating the steps (iii) and (iv) to form a plurality of the optic elements having the pattern.
15. The method of claim 2, wherein the wafer comprises silicon (Si) deposited on a silicon dioxide (SiO₂) substrate.
16. The method of claim 4, wherein the soft material comprises a polymer stamp material.
17. The method of claim 1, wherein the resin layer comprises a photo-curable resin, the photo-curable resin includes 2-methoxy-1-methylethyl acetate, ethoxylated bisphenol A diacrylate and 2-(2-((oxo(phenyl)acetyl)oxy)thoxy)ethyl oxo(phenyl)acetate.
18. The method of claim 1, wherein an etching selectivity of the resin layer to the metallic layer is equal to or greater than 5 to 1.
19. The method of claim 1, wherein the optic element comprises nanopillars having an aspect ratio of equal to or greater than 5 to 1.
20. The method of claim 1, wherein an etching selectivity of the metallic layer to the film structure is equal to or greater than 5 to 1.