OPTICAL SYSTEM, METHOD OF FORMING THE SAME, METHOD OF DIRECT LASER WRITING

TECHNICAL FIELD

[0001] Various embodiments of this disclosure may relate to an optical system. Various embodiments of this disclosure may relate to a method of forming an optical system. Various embodiments of this disclosure may relate to a method of direct laser writing.

BACKGROUND

[0002] Nano-patterning is a critical step in many materials and device applications. Many nano-patterning techniques have been developed, e.g., electron-beam lithography (EBL) and focused ion beam (FIB) lithography, dip-pen lithography and scanning probe lithography, which have high resolution, but are costly and have low throughputs. Nanoimprint lithography (NIL) offers a low cost and high throughput approach for large area patterning but still needs improvement on accuracy, alignment, and uniformity, etc. Also, the master mold has to be created by other lithographic methods.

[0003] Optical or photolithography has been the dominant patterning technology in semiconductor industries for several decades, due to its large scale and high throughput characteristics. By pushing the light wavelength used in photolithography to deep UV (DUV) and extreme UV (EUV), the resolution can compete with the electron and ion based lithography. However, optical or photolithography faces escalating cost of associated tools and processes involved.

[0004] Direct laser writing (DLW) is a maskless lithographic technique, which is not only used in semiconductor industry for mask fabrication, but is also a very important lab tool for

scientists working in nanotechnology. The resolution is a crucial factor for a DLW system due to the need for miniaturization in various applications like optics, microelectromechanical systems (MEMS), sensors, etc.

[0005] However, due to the fundamental diffraction limitation (Rayleigh criteria - $0.61\lambda/NA$) of conventional objective lenses used in the DLW systems, the lithographic resolution is not sufficient for many applications, especially higher value-added applications. The minimum feature size of DLW in the market is above 300 nm. This pain point is highly limiting the market space for DLW systems.

SUMMARY

[0006] Various embodiments may relate to an optical system. The optical system may include a laser source for emitting one or more laser beams. The optical system may also include a metalens. The optical system may further include a first stage mounting the metalens. The optical system may additionally include a first motor configured to move the first stage. The optical system may further include a second stage for holding a sample. The optical system may also include a second motor configured to move the second stage. The optical system may include an objective. The optical system may further include a third stage configured to hold the objective. The optical system may additionally include a third motor configured to move the third stage. The optical system may also include a detector. The optical system may include a screen including or defining a pinhole, the screen arranged between the objective and the detector. The optical system may also include a processor in electrical communication with the first motor, the second motor and the third motor. The metalens may be configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process. The processor may be configured to determine a distance between the metalens and the sample based on an image captured by the detector before the direct laser

writing process. The processor may be further configured to control the second motor to move the second stage for controlling an exposure time of the sample during the direct laser writing process.

[0007] Various embodiments may relate to a method of forming an optical system. The method may include providing a laser source for emitting one or more laser beams. The method may include forming or providing a metalens. The method may also include providing a first stage to mount the metalens. The method may further include providing a first motor configured to move the first stage. The method may additionally include providing a second stage for holding a sample. The method may include providing a second motor configured to move the second stage. The method may also include provide an objective. The method may also include providing a third stage configured to hold the objective. The method may further include providing a third motor configured to move the third stage. The method may additionally include providing a detector. The method may also include providing a screen including a pinhole, the screen arranged between the objective and the detector. The method may further include providing a processor in electrical communication with the first motor, the second motor and the third motor. The metalens may be configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process. The processor may be configured to determine a distance between the metalens and the sample based on an image captured by the detector before the direct laser writing process. The processor may be further configured to control the second motor to move the second stage for controlling an exposure time of the sample during the direct laser writing process.

[0008] Various embodiments may relate to a method of direct laser writing. The method may include providing an optical system. The optical system may include a laser source for emitting one or more laser beams. The optical system may also include a metalens. The optical system may further include a first stage mounting the metalens. The optical system may

additionally include a first motor configured to move the first stage. The optical system may also include a second stage for holding a sample. The optical system may further include an objective. The optical system may additionally include a third stage configured to hold the objective. The optical system may also include a third motor configured to move the third stage. The optical system may further include a detector. The optical system may additionally include a screen including a pinhole, the screen arranged between the objective and the detector. The optical system may also include a processor in electrical communication with the first motor, the second motor and the third motor. The method may include providing the sample. The method may also include determining a distance between the metalens and the sample based on an image captured by the detector before a direct laser writing process in which the metalens is configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample. The method may additionally include controlling an exposure time of the sample during the direct laser writing process using the second motor to move the second stage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 is a general illustration of an optical system according to various embodiments.

FIG. 2 is a general illustration of a method of forming an optical system according to various embodiments.

FIG. 3 is a general illustration of a method of direct laser writing according to various embodiments.

FIG. 4 illustrates the resolution, costs and writing speeds of various lithographic method, including direct laser writing (DLW) according to various embodiments.

FIG. 5 shows scanning electron microscopy (SEM) images of two types of two-dimensional lenses: (a) a scanning electron microscopy (SEM) image of a Fresnel zone plate (FZP) lens according to various embodiments; and (b) a scanning electron microscopy (SEM) image of a supercritical lens (SCL) lens according to various embodiments.

FIG. 6 shows a schematic of an optical system according to various embodiments.

FIG. 7 shows (a) an optical image of a snake ladder pattern with the feature size around 270 nm generated by the optical system according to various embodiments; and (b) an atomic force microscopy (AFM) measurement of the snake ladder pattern generated by the optical system according to various embodiments.

FIG. 8 shows (a) a scanning electron microscopy (SEM) image of a dense grating pattern written by the optical system according to various embodiments; and (b) a zoom-in view of a portion of the image shown in (a).

FIG. 9 illustrates potential applications for direct laser writing using the optical system according to various embodiments.

FIG. 10 is a table comparing an embodiment and two conventional systems.

DESCRIPTION

[0010] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practised. These embodiments are described in sufficient detail to enable those skilled in the art to practise the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various

embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0011] Embodiments described in the context of one of the optical systems are analogously valid for the other optical systems. Similarly, embodiments described in the context of a method are analogously valid for an optical system, and vice versa.

[0012] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0013] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements.

[0014] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a reasonable variance.

[0015] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0016] Various embodiments may relate to an optical system including a planar metalens for laser writing. Various embodiments may address the issues faced by conventional lithographic systems.

[0017] FIG. 1 is a general illustration of an optical system according to various embodiments. The optical system may include a laser source 102 for emitting one or more laser beams. The optical system may also include a metalens 104. The optical system may further include a first stage 106 mounting the metalens 104. The optical system may additionally include a first motor 108 configured to move the first stage 106. The optical system may further

include a second stage 110 for holding a sample. The optical system may also include a second motor 112 configured to move the second stage 110. The optical system may include an objective 114 (i.e. objective lens). The optical system may further include a third stage 116 configured to hold the objective 114. The optical system may additionally include a third motor 118 configured to move the third stage 116. The optical system may also include a detector 120. The optical system may include a screen 122 including or defining a pinhole, the screen 122 arranged between the objective 114 and the detector 120. The optical system may also include a processor 124 in electrical communication with the first motor 108, the second motor 112 and the third motor 118. The metalens 104 may be configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process. The processor 124 may be configured to determine a distance between the metalens 104 and the sample based on an image captured by the detector 120 before the direct laser writing process. The processor 124 may be further configured to control the second motor 112 to move the second stage 110 for controlling an exposure time of the sample during the direct laser writing process.

[0018] For avoidance of doubt, FIG. 1 serves to illustrate some of the features of various embodiments, and is not intended to limit the arrangement, sizes, shapes, orientation etc. of the various features.

[0019] In various embodiments, the optical system may be or may include a confocal microscope. The optical system may include three stages 106, 110 and 116 configured to be actuated by motors 108, 112, 118 respectively. The optical system may also include a laser source 102, a metalens 104, a screen 122 with a pinhole, and a detector 120. During operation, the first stage 106 may move the first stage holding the metalens 104, the second motor 112 may move the second stage holding the sample, while the third motor 118 may move the third stage 116 holding the objective 114. The optical system may also include a processor 124

configured to control the first motor 108, the second motor 112 and the third motor 118. In various embodiments, the processor 124 may be part of the confocal microscope, while in various other embodiments, the processor 124 may be external to the confocal microscope.

[0020] In various embodiments, the metalens 104 may be a planar or two dimensional metalens. In various embodiments, the metalens 104 may be a super oscillation lens (also referred to as a super oscillatory lens). In various embodiments, the super oscillation lens may include a plurality of metal rings forming a concentric arrangement. The metal rings may be substantially be opaque to the laser beams. In other words, the metal rings may prevent the laser beams from being transmitted through. However, laser beams passing through the transparent regions between the metal rings may be allowed to be transmitted through. In various other embodiments, the super oscillation lens may include a plurality of grooves extending from a first surface of the lens through an opaque substrate to a second surface of the lens opposite the first surface, the plurality of grooves forming a plurality of concentric ring structures. The super oscillation lens may be configured to generate a sub-diffraction limit focusing spot upon the one or more laser beams incident onto the lens.

[0021] In various other embodiments, the metalens 104 may be a planar diffraction lens, such as a Fresnel zone plate (FZP) lens or a supercritical lens (SCL). A Fresnel zone plate (FZP) lens may be a lens that includes a plurality of concentric rings (referred to as Fresnel zones), which alternate to being substantially opaque to the laser beams and being substantially transparent to the laser beams. A supercritical lens (SCL) may include a plurality of concentric rings that are substantially transparent to the laser beams.

[0022] In various embodiments, the focal spot may be a diffraction unlimited focal spot. In other words, the size of the focal spot of the metalens 104 may not be limited by diffraction. The metalens 104 may show sub-diffraction limit focusing. In various embodiments, the metalens 104 may employ magnitude modulation.

[0023] In various embodiments, the laser source may be a 405 nm laser source. The laser source may generate laser beams of 405 nm. The one or more laser beams may be continuous wave (CW) laser beams. Various embodiments may be able to achieve a feature size of only 180 nm on photoresist using a 405 nm laser source. In various other embodiments, the laser source may be configured to generate laser beams of any other suitable wavelengths. In various embodiments, the one or more laser beams may be any wavelength or range of wavelengths in the visible region (400 nm to 700 nm). In various embodiments, the laser beams may be any wavelength or range of wavelengths in the infrared region or ultraviolet region (e.g. in the deep ultraviolet region of about 200 nm to 280 nm). In various embodiments, any suitable laser source may be used. Various embodiments may be able to achieve a feature size of less than 180 nm.

[0024] In various embodiments, the first motor 108, the second motor 112 and the third motor 118 may be piezoelectric motors.

[0025] In various embodiments, the metalens 104 may include a substrate substantially transparent to the one or more laser beams. The metalens 104 may include a patterned metal layer on the substrate, the patterned metal layer configured to allow at least the portion of the one or more laser beams to pass through during the direct laser writing process, while blocking a remaining portion of the one or more laser beams. The patterned metal layer may be substantially opaque to the one or more laser beams.

[0026] For avoidance of doubt, an element being substantially transparent to the one or more laser beams may refer to the element allowing the laser beams to pass through without significant reduction in magnitude, e.g. more than 50%, e.g. more than 80%, e.g. more than 90%, e.g. more than 95%, e.g. more than 99%. Conversely, an element being substantially opaque to the one or more laser beams may refer to the element being able to block the laser beams, or allowing only the laser beams to pass through with substantial reduction in

magnitude, e.g. less than 20%, e.g. less than 10%, e.g. less than 5%, e.g. less than 1%, e.g. less than 0.1%.

[0027] The detector 120 may be a charge-coupled device (CCD) or a photodiode.

[0028] In various embodiments, the processor 124 may include a suitable software to control the movement of stages 106, 110, 118 by controlling motors 108, 112, 118.

[0029] FIG. 2 is a general illustration of a method of forming an optical system according to various embodiments. The method may include, in 202, providing a laser source for emitting one or more laser beams. The method may include, in 204, forming or providing a metalens. The method may also include, in 206, providing a first stage to mount the metalens. The method may further include, in 208, providing a first motor configured to move the first stage. The method may additionally include, in 210, providing a second stage for holding a sample. The method may include, in 212, providing a second motor configured to move the second stage. The method may also include, in 214, provide an objective. The method may also include, in 216, providing a third stage configured to hold the objective. The method may further include, in 218, providing a third motor configured to move the third stage. The method may additionally include, in 220, providing a detector. The method may also include, in 222, providing a screen including a pinhole, the screen arranged between the objective and the detector. The method may further include, in 224, providing a processor in electrical communication with the first motor, the second motor and the third motor. The metalens may be configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process. The processor may be configured to determine a distance between the metalens and the sample based on an image captured by the detector before the direct laser writing process. The processor may be further configured to control the second motor to move the second stage for controlling an exposure time of the sample during the direct laser writing process.

[0030] For avoidance of doubt, FIG. 2 serves to illustrate some of the various steps according to various embodiments, and is not intended to limit the sequence of the various steps. For instance, step 202 can occur before, at the same time, or after step 204.

[0031] In various embodiments, the metalens may be formed by focused ion beams (FIB), electron beam lithography (EBL) or photon lithography.

[0032] In various embodiments, the metalens may be formed based on parameters provided by binary particle-swarm-optimization algorithm. Binary particle-swarm-optimization algorithm may be used to construct the supercritical focusing at a predefined distance (z=f) and spot size in terms of full width at half maximum (FWHM) with certain wavelength. The wavelength can be altered in the algorithm. The merit function in the focal region may be defined. Then, the diffraction field may be calculated by scalar angular spectrum method which gives good approximation. Due to radial symmetry of the ring structures, the calculation may be simplified to a one dimensional (1D) Hankel transform for saving memory and time. The final design may be achieved when the intensity variance between the calculated field and target merit function is minimized.

[0033] In various embodiments, the metalens may be a super oscillation lens. In various embodiments, the metalens may be a Fresnel zone plate lens or a super critical lens.

[0034] In various embodiments, the metalens may have a diffraction unlimited focal spot.

[0035] In various embodiments, the laser source may be a 405 nm laser source. In various other embodiments, the laser source may be configured to generate one or more laser beams of any other suitable wavelengths.

[0036] In various embodiments, the first motor, the second motor and the third motor may be piezoelectric motors.

[0037] In various embodiments, the metalens may include a substrate transparent to the one or more laser beams. The metalens may include a patterned metal layer on the substrate, the

patterned metal layer configured to allow at least the portion of the one or more laser beams to pass through during the direct laser writing, while blocking a remaining portion of the one or more laser beams.

[0038] FIG. 3 is a general illustration of a method of direct laser writing according to various embodiments. The method may include, in 302, providing an optical system. The optical system may include a laser source for emitting one or more laser beams. The optical system may also include a metalens. The optical system may further include a first stage mounting the metalens. The optical system may additionally include a first motor configured to move the first stage. The optical system may also include a second stage for holding a sample. The optical system may further include an objective. The optical system may additionally include a third stage configured to hold the objective. The optical system may also include a third motor configured to move the third stage. The optical system may further include a detector. The optical system may additionally include a screen including a pinhole, the screen arranged between the objective and the detector. The optical system may also include a processor in electrical communication with the first motor, the second motor and the third motor. The method may include, in 304, providing the sample. The method may also include, in 306, determining a distance between the metalens and the sample based on an image captured by the detector before a direct laser writing process in which the metalens is configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample. The method may additionally include, in 308, controlling an exposure time of the sample during the direct laser writing process using the second motor to move the second stage.

[0039] In various embodiments, the sample may include a photoresist. The photoresist may be any suitable photoresist.

[0040] In various embodiments, writing onto the sample may include controlling the optical system such that at least the portion of the one or more laser beams is incident on a part of the photoresist to polymerize the part of the photoresist.

[0041] Various embodiments may be used for high-resolution direct laser writing for optical applications, such as patterning diffractive optical elements (DOE) and other flat optics.

[0042] In various embodiments, the metalens may form a focal spot having a needle shape onto the sample.

[0043] Various embodiments may be used to write or form arbitrary patterns on the sample, e.g. photoresist. In various embodiments, the metalens may directly focus (i.e. without passing through another optical element) a portion of the one or more laser beams onto the sample, while blocking a remaining portion of the one or more laser beams.

[0044] FIG. 4 illustrates the resolution, costs and writing speeds of various lithographic method, including direct laser writing (DLW) according to various embodiments.

[0045] Various embodiments may relate to a super oscillation lens working at the supercritical condition ($0.38\lambda/NA$) (λ is the operating wavelength, and NA is the numerical aperture) by using the super-oscillation concept, and which has shown sub diffraction limit focusing, no significant side lobes and long working distance. Various embodiments may be promising for super resolution scanning optical confocal imaging and optical lithography. Various embodiments may relate to using super oscillation lens for direct laser writing (DLW) optical lithography. By incorporating the super oscillation lens into an optical confocal microscope with moving stages and using a 405 nm laser, patterns with the feature size of only 180 nm have been created on photoresist, which is much better than the benchmarked product Heidelberg DWL 66+ that can produce 300 nm features.

[0046] Super-oscillation lens is the core component in this super-resolution optical lithography technology. FIG. 5 shows scanning electron microscopy (SEM) images of two

types of two-dimensional lenses: (a) a scanning electron microscopy (SEM) image of a Fresnel zone plate (FZP) lens according to various embodiments; and (b) a scanning electron microscopy (SEM) image of a supercritical lens (SCL) lens according to various embodiments. The two types of 2D lens may work at the wavelength of 405nm. The full width at half maximum (FWHM) of the Fresnel zone plate (FZP) lens may be 0.65λ, and the full width at half maximum (FWHM) of the supercritical lens (SCL) lens may be 0.46λ.

[0047] FZP lens may be designed with a longer working distance and a larger focal spot comparing to SCL. The longer working distance may benefit the positioning processes between the 2D lens and photoresist layer, but may lower the resolution of the direct laser writing (DLW). The above lenses may be employed to form patterns with different required feature sizes on photoresist. Various embodiments may be fabricated by focused ion beam (FIB), while in terms of mass production, electron beam lithography or photon lithography may both be suitable to fabricate the lenses.

[0048] FIG. 6 shows a schematic of an optical system according to various embodiments. The optical system may be a setup based on a photon scanning tunnelling microscopy (PSTM) system. The optical system may include a laser source 602, e.g. a 25 mW laser diode, for emitting one or more laser beams (e.g. at 405 nm), and a metalens (or 2D lens) 604. The optical system may include a first stage 606 mounting the metalens 604. More specifically, the optical system may include a lens holder 626, which may in turn be mounted on the first stage 606. The first stage 606 may be a piezoelectric stage, i.e. the stage 606 may be actuated by a first piezoelectric motor (not shown in FIG. 6).

[0049] The optical system may also include a second stage 610 for holding a sample (e.g. photoresist). The optical system may include a second piezoelectric motor (not shown in FIG. 6) configured to move the second stage 610. The optical system may also include an objective 614. The optical system may also include a third piezoelectric stage 616 configured to hold the

objective 614, and a third piezoelectric motor (not shown in FIG. 6) configured to move the third stage. The optical system may also include a detector 620, and a screen (not shown in FIG. 6) including or defining a pinhole 622, the screen arranged between the objective 614 and the detector 620. The optical system may also include a processor 624 in electrical communication with the first motor, the second motor and the third motor.

[0050] During operation, the first stage 606 mounting the lens holder 626 with the 2D lens 604 may be adjusted (using the first piezoelectric motor) to align with the one or more laser beams emitting from the laser source 602. The optical system may include a mirror 630 to change a direction of the one or more laser beams before the one or more laser beams are directed to the 2D lens 604. During the alignment phase of operation, the one or more laser beams passing from the 2D lens 604 through the objective 614, the tube lens 628 and the pinhole 622 and incident on the detector 620 (making up a confocal microscope) may be used to determine a desired distance between the 2D lens 604 and the sample. The first piezoelectric motor may move the first stage 606 until the distance between the 2D lens 604 and the sample is the desired distance. The desired distance may be the distance between the 2D lens 604 and the sample corresponding to a desired focal spot (or focal point) that would be formed on the sample during the the direct laser writing process. The desired focal spot (or focal point) may be determined or measured by the detector 620. After the distance is set, during the writing phase, the second stage 610 holding a sample (e.g. photoresist) may be moved to control the exposure of the sample (e.g. photoresist). Patterns may be formed on a surface of the sample (e.g. photoresist). The third stage 616 holding the objective 614 may be also moved during operation. The objective 614 may be moved for focusing on items such as the 2D lens 604 and the sample (e.g. photoresist wafer).

[0051] In the experiment, the samples are silica substrates spin coated with AZ5214e photoresist at 6,000 rpm. The thickness of the photoresist films are around 1 μm to 1.5 μm. Pre-

bake on a hot plate at 90 °C for 60 s has been carried out for all samples exposed to the laser beam. The exposed patterns are developed in an AZ developer diluted with water in the ratio 1 : 3 for 10 s. A thinner photoresist may help to increase the writing resolution.

[0052] The lithographic patterns produced by the optical system are shown below. FIG. 7 shows (a) an optical image of a snake ladder pattern with the feature size around 270 nm generated by the optical system according to various embodiments; and (b) an atomic force microscopy (AFM) measurement of the snake ladder pattern generated by the optical system according to various embodiments. The depth of the structures is around 40 nm as indicated by AFM. The writing speed is set as 1μm/s and the incident laser power is set at 2.3 μW. The 2D lens used here has a numerical aperture (NA) of 0.66 and a working distance of 50 μm. Considering PSTM could be damaged by high power laser beam, relative low laser power and slow writing speed were employed. Various embodiments may relate to a specific lithography system adapted to higher laser power, which may increase writing speeds.

[0053] FIG. 8 shows (a) a scanning electron microscopy (SEM) image of a dense grating pattern written by the optical system according to various embodiments; and (b) a zoom-in view of a portion of the image shown in (a). The dense grating structure may be formed by a 2D lens with numerical aperture (NA) of 0.89 and a working distance of 20 μm. The laser power and writing speed used may be similar to that used to write the patterns shown in FIG. 7. The pattern includes lines with 2 μm pitch distance. As shown in FIG. 8(b), there is a linewidth of around 180 nm. The results may prove the resolution advantages of the optical system enabled by he 2D lens over products commercially available in market currently, such as Heidelberg DWL 66+ (minimum feature size 300 nm). By employing shorter wavelength laser such as deep UV, the resolution may be further enhanced.

[0054] FIG. 9 illustrates potential applications for direct laser writing using the optical system according to various embodiments. The next phase of optics for consumer electronics

is flat optics which show an overwhelming advantage in performance compared with traditional optics, while most of these flat optics, e.g. diffractive optical elements (DOE), require more advanced optical lithography resolution to 100 - 300 nm. There is no economical solution in the market now. Various embodiments may enable optical systems to achieve a resolution of 100 - 300 nm. Various embodiments may allow the entering of the camera optics market to drive the 'flat transformation'.

[0055] The lithography method used in the semiconductor industry is optical projection lithography which requires masks for the mass production of chips. The cost of a set of masks for producing a chip could be more than 2 million, and yet in most cases only a few wafers will be produced. Therefore, for low volume production, the DLW could be ideal alternative to save costs and enable more flexible production.

[0056] Due to the research trend of smaller structural features and bigger pattern areas, the research industry is in need for a lithography tool with higher writing speed, higher resolution, and lower costs. Various embodiments may be able to satisfy this need.

[0057] FIG. 10 is a table comparing an embodiment and two conventional systems.

[0058] Various embodiments may achieve sub-diffraction limit focusing for lithography. Various embodiments may improve resolution. Although there are many approaches to go, such as using shorter wavelengths and a higher NA objective etc., the fundamental issue with conventional objective lenses used in DLW systems is that they are diffraction limited (Rayleigh criteria $0.61\lambda/NA$). This limitation suppresses any other attempts for higher lithography resolution in DLW. Various embodiments may employ the super oscillation concept to design the 2D lens with sub-diffraction limit focusing for DLW, which breaks the resolution limit.

[0059] By incorporating the 2D lens into an optical confocal microscope with moving stages and using a 405 nm laser, patterns with feature size of only 180 nm have been created on

photoresist, which is much better than the resolution achieved by benchmarked product Heidelberg DWL 66+ that can produce 300 nm features. This can be further improved via using shorter wavelengths and putting the lens in higher refractive index environment for larger NA.

[0060] The focal spot of the 2D lens may be needle shape with depth of focus in microns, which is good for fabricating high aspect ratio structures. This cannot be achieved by a conventional objective lens.

[0061] The conventional objective lens for optical lithography cannot provide the sub-diffractive limit focusing spot, which is ruled by fundamental physics. Several methods can improve the lithography resolution, such as using shorter wavelengths (ArF 193nm for stepper), enlarging the NA by using immersion objective or optimizing the photoresist and lithography process. However, these alternative solutions are still diffractive limited.

[0062] Various embodiments involving diffractive unlimited lens may have advantages over these alternative solutions. Further, diffractive unlimited 2D lens may also be combined with these alternative solutions to achieve even better lithography resolution than conventional lens.

[0063] Various embodiments may use knowledge and experience in optical design, optics packaging, automatic control, and optoelectronic system design to replace the traditional spherical lens with the 2D lens in the DLW system for achieving higher performance, more compact system and lower cost.

[0064] By "comprising" it is meant including, but not limited to, whatever follows the word "comprising". Thus, use of the term "comprising" indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0065] By "consisting of" is meant including, and limited to, whatever follows the phrase "consisting of". Thus, the phrase "consisting of" indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0066] The inventions illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms "comprising", "including", "containing", etc. shall be read expansively and without limitation. Additionally, the terms and expressions employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the inventions embodied therein herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention.

[0067] By "about" in relation to a given numerical value, such as for temperature and period of time, it is meant to include numerical values within 10% of the specified value.

[0068] The invention has been described broadly and generically herein. Each of the narrower species and sub-generic groupings falling within the generic disclosure also form part of the invention. This includes the generic description of the invention with a proviso or negative limitation removing any subject matter from the genus, regardless of whether or not the excised material is specifically recited herein.

[0069] Other embodiments are within the following claims and non- limiting examples. In addition, where features or aspects of the invention are described in terms of Markush groups, those skilled in the art will recognize that the invention is also thereby described in terms of any individual member or subgroup of members of the Markush group.

CLAIMS

1. An optical system comprising:

a laser source for emitting one or more laser beams;

a metalens;

a first stage mounting the metalens;

a first motor configured to move the first stage;

a second stage for holding a sample;

a second motor configured to move the second stage;

an objective;

a third stage configured to hold the objective;

a third motor configured to move the third stage;

a detector;

a screen comprising a pinhole, the screen arranged between the objective and the detector; and

a processor in electrical communication with the first motor, the second motor and the third motor;

wherein the metalens is configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process;

wherein the processor is configured to determine a distance between the metalens and the sample based on an image captured by the detector before the direct laser writing process; and

wherein the processor is further configured to control the second motor to move the second stage for controlling an exposure time of the sample during the direct laser writing process.

2. The optical system according to claim 1,

wherein the metalens is a super oscillation lens.

3. The optical system according to claim 1,

wherein the metalens is Fresnel zone plate lens or a super critical lens.

4. The optical system according to claim 1,

wherein the metalens has a diffraction unlimited focal spot.

5. The optical system according to claim 1,

wherein the laser source is a 405 nm laser source.

6. The optical system according to claim 1,

wherein the first motor, the second motor and the third motor are piezoelectric motors.

7. The optical system according to claim 1,

wherein the metalens comprises a substrate transparent to the one or more laser beams; and

wherein the metalens comprises a patterned metal layer on the substrate, the patterned metal layer configured to allow at least the portion of the one or more laser beams to pass through during the direct laser writing process, while blocking a remaining portion of the one or more laser beams.

8. A method of forming an optical system, the method comprising:

providing a laser source for emitting one or more laser beams;

forming a metalens;

providing a first stage to mount the metalens;

providing a first motor configured to move the first stage;

providing a second stage for holding a sample;

providing a second motor configured to move the second stage;

providing an objective;

providing a third stage configured to hold the objective;

providing a third motor configured to move the third stage;

providing a detector;

providing a screen comprising a pinhole, the screen arranged between the objective and the detector; and

providing a processor in electrical communication with the first motor, the second motor and the third motor;

wherein the metalens is configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample during a direct laser writing process;

wherein the processor is configured to determine a distance between the metalens and the sample based on an image captured by the detector before the direct laser writing process; and

wherein the processor is further configured to control the second motor to move the second stage for controlling an exposure time of the sample during the direct laser writing process.

9. The method according to claim 8,

wherein the metalens is formed by focused ion beams, electron beam lithography or photon lithography.

10. The method according to claim 8,

wherein the metalens is formed based on parameters provided by binary particle-swarm-optimization algorithm.

11. The method according to claim 8,

wherein the metalens is a super oscillation lens.

12. The method according to claim 8,

wherein the metalens is a Fresnel zone plate lens or a super critical lens.

13. The method according to claim 8,

wherein the metalens has a diffraction unlimited focal spot.

14. The method according to claim 8,

wherein the laser source is a 405 nm laser source.

15. The method according to claim 8,

wherein the first motor, the second motor and the third motor are piezoelectric motors.

16. The method according to claim 8,

wherein the metalens comprises a substrate transparent to the one or more laser beams; and

wherein the metalens comprises a patterned metal layer on the substrate, the patterned metal layer configured to allow at least the portion of the one or more laser beams to pass through during the direct laser writing, while blocking a remaining portion of the one or more laser beams.

17. A method of direct laser writing, the method comprising:

providing an optical system comprising:

a laser source for emitting one or more laser beams;

a metalens;

a first stage mounting the metalens;

a first motor configured to move the first stage;

a second stage for holding a sample;

a second motor configured to move the second stage;

an objective;

a third stage configured to hold the objective;

a third motor configured to move the third stage;

a detector;

a screen comprising a pinhole, the screen arranged between the objective and the detector; and

a processor in electrical communication with the first motor, the second motor and the third motor;

providing the sample to the second stage;

determining a distance between the metalens and the sample based on an image captured by the detector before a direct laser writing process in which the metalens is configured to allow at least a portion of the one or more laser beams to pass through to write onto the sample; and

controlling an exposure time of the sample during the direct laser writing process using the second motor to move the second stage.

18. The method according to claim 17,

wherein the sample comprises a photoresist.

19. The method according to claim 18,

wherein writing onto the sample comprises controlling the optical system such that at least the portion of the one or more laser beams is incident on a part of the photoresist to polymerize the part of the photoresist.

20. The method according to claim 17,

wherein the metalens forms a focal spot having a needle shape onto the sample.