$$T(x, y) = \tag{6}$$

$$\tau[E_1(x)] \times \tau[E_2(y)] = \frac{a_x a_y}{4} \sum_{n=-\infty}^{\infty} \left[\frac{\sin\left(\frac{2\pi n a_x \sin(\theta_x)}{\lambda}\right)}{\left(\frac{2\pi n a_x \sin(\theta_x)}{\lambda}\right)} e^{i\frac{4\pi n x \sin(\theta_x)}{\lambda}} \right] \times$$

$$\sum_{n'=-\infty}^{\infty} \left[\frac{\sin\left(\frac{2\pi n' a_y \sin(\theta_y)}{\lambda}\right)}{\left(\frac{2\pi n' a_y \sin(\theta_y)}{\lambda}\right)} e^{\frac{i4\pi' n y \sin(\theta_y)}{\lambda}} \right]$$

Support for “spatial frequencies”

-- and --

“combining nonlinear functions of intensity . . . ”

FIGS. 7A–7B show an experimental realization of this pattern. A Si wafer was coated with a thin Si_3N_4 film and with a first photoresist layer. A two-beam interferometric exposure was used to define a line:space array in this first photoresist layer. The pattern was developed, transferred into the nitride film, and the remaining photoresist removed. An exemplary resulting pattern in the nitride layer is shown in FIG. 7A. A second photoresist layer was then applied to the wafer and a second two-beam interferometric exposure, substantially at right angles to the first exposure pattern, was suitably applied and developed. FIG. 7B shows an exemplary resulting pattern: the vertical lines are in the nitride, the horizontal lines are in the second photoresist layer. Together the two mask patterns provide a multiplication of the individual images that have been operated on independently with the nonlinear thresholding responses of the two photoresist layers. The composite mask pattern shows substantially right angles at the corners as predicted by Eq. 6 and in FIG. 6B.

Support for “first mask material”

Support for “combined mask . . . ”

FIGS. 8A–8C show exemplary results from a similar calculation for the prototypical array structure of FIG. 1. FIG. 8A shows an exemplary result of suitably applying a thresholding nonlinearity to a simple two-beam interferometric lithography exposure with a CD of 130 nm and a pitch of 260 nm. FIG. 8B shows an exemplary pattern obtained from a conventional (incoherent illumination) optical lithography exposure of the mask corresponding to FIG. 1 [I-line (365 nm) exposure wavelength and 0.5 NA lens]. While the optical exposure typically cannot substantially resolve the 130-nm CD structures, it does provide information that can be used to suitably restrict the extent of the interferometric exposure which exists over the entire field. Finally, FIG. 8C shows an exemplary result of multiplying the two patterns to get the final result, thereby showing the dramatic improvement in the profiles. This example preferably involves a combination of an interferometric lithography exposure and an imaging optical exposure, while the prior example consisted of two interferometric lithography exposures.

Support for “parts of said first mask layer”

As mentioned, the present invention relates to the use of nonlinear processing suitably combined with multiple exposures to extend the range of spatial frequencies beyond those available with conventional single or additive exposure techniques. In implementing the nonlinear processing and multiple exposures, the present invention preferably incorporates any suitable combination of interferometric lithography, imaging optical and/or other exposure techniques. Thus, a number of processing sequences exist that are preferably used to achieve this sequential thresholding of each exposure and multiplication of the resulting patterns.

In a preferred embodiment, a sacrificial layer, such as, for example a SiO_2 or Si_3N_4 layer, is used with additional processing between the two exposures. More particularly, following a suitable interferometric lithography exposure and develop of a first pattern in a first photoresist layer, the resulting pattern is transferred into the sacrificial layer by a suitable etching step. Any remaining photoresist from the first photoresist layer is then removed and the wafer is then preferably coated with a second photoresist layer and a second exposure and develop sequence is suitably carried out to transfer a second pattern into this second photoresist layer. In an alternative embodiment, this second exposure is an imaging optical exposure. A second etch step is preferably carried out to transfer the combined pattern into the underlying wafer layers. The second etch step preferably uses a combined etch mask, parts of which are preferably comprised of the nitride layer and parts of which are comprised of the undeveloped photoresist layer. Thus, in a preferred embodiment, the combined etch mask provides the multiplication operation. Finally, the remaining mask layers, both photoresist and sacrificial material, are preferably removed. While the aforementioned exemplary process is set forth, it will be appreciated by one of ordinary skill in the art of semiconductor processing that many variants on this basic process exist. For example, in an alternative embodiment, an additive step, such as deposition and lift-off, is suitably used in place of one or another of the etch steps recited above. In another alternative embodiment, damascene (etching, deposition and polishing to produce an inlaid structure) processes are incorporated into the process. In another alternative embodiment, in certain process flows, different sacrificial layers, such as, for example metals, poly-Si, polymers and the like, are incorporated into the process.

Support for “parts of said first mask layer”

In practice, to reduce costs, it is typically desirable to reduce the number and complexity of processes necessary to achieve the desired structure. In particular, it is desirable to create the same combination of nonlinearities in a single photolithography sequence without requiring additional etch or deposition steps. To achieve the same combination without additional steps, a preferred embodiment of the present invention incorporates image reversal and/or multilayer resist systems incorporating two exposures [see, for example, *Introduction to Microlithography, Second Edition*, L. F. Thompson, C. G. Willson, M. J. Bowden, eds. Amer. Chem. Soc. Washington, D.C., 25 1994, pp. 184–190, 232–251 and 347–371]. Conventionally, image reversal is often used to create a negative-tone image with a positive resist by exposing the resist (which is specially formulated for image reversal) with a first exposure. The first exposure suitably frees the bound photoactive compound (PAC) in the resist. Depending on the resist formulation, the freed PAC is suitably removed from the resist film with a bake step or an exposure to an appropriate chemical ambient. Next, a second exposure, usually a flood exposure without any spatial information, is suitably used to free the remaining bound PAC in the areas not exposed in the first exposure. Finally, a conventional develop step results in a negative tone image. Multilayer resist systems utilize a similar sequence (expose, process, expose, develop) with the exposure wavelengths chosen to affect specific films within the multilayer resist film stack.

In both processes, the first exposure and intermediate process steps suitably provide a nonlinear response, while the second develop step suitably provides a second nonlinear response. In a preferred embodiment of the present invention, the aforementioned flood exposure step is suitably replaced by a second exposure containing spatial information. In a preferred embodiment, the second exposure is preferably an interferometric exposure. In an alternative embodiment, the second exposure is an imaging optical exposure. The replacement of the flood exposure by a second exposure with spatial information results in the desired sequence of nonlinear steps.

In an alternative embodiment, the combination of nonlinearities is suitably achieved by a multi-layer resist process such as discussed by Willson in the above reference. A photoresist sensitive at longer wavelengths is preferably deposited onto the wafer first, followed by a photoresist sensitive at shorter wavelengths. The layers include any suitable photoresist, but in this embodiment, an I-line resist is used for the bottom layer and a 248-nm resist is used for the top layer. The top resist is preferably selected to be transparent to the I-line wavelength used to expose the bottom resist, and is preferably chosen to be sufficiently absorbing at the 248-nm wavelength to substantially block any light from the exposure at this wavelength from reaching the bottom layer. In an alternative embodiment, a non-photosensitive buffer layer is suitably deposited between the two layers to assist in preserving the integrity of the individual photoresist layers. Consequently, two independent nonlinearities (thresholding) and a layering (multiplication) of the two exposure masks exists. Alternatively, the two sensitivities are suitably combined into a single resist with both positive and negative tonalities, as demonstrated by Hinsberg et al. [W. D. Hinsberg, S. A. MacDonald, L. A. Pederson and C. G. Willson, "A Lithographic Analog of Color Photography: Self-Aligning Photolithography Using a Resist with Wavelength-Dependent Tone," Jour. Imaging Sci. 33, 129–135 (1989).]

In a second preferred embodiment, two nonlinear functions of intensity are added to create spatial frequencies in the final pattern that are not present in either of the individual exposures, resulting in frequency multiplying. More particularly, the use of spatial-frequency multiplied interferometric lithography for the reduction in pitch for the array structure of FIG. **1** will now be described in more detail in FIGS. **9A–9E**. FIGS. **9A–9E** show a preferred embodiment for a sequence using subtractive fabrication processes that results in an approximate factor of two increase in the spatial period; i.e. a reduction of a factor of two in the pitch. With respect to FIG. **9A**, a preferred exemplary structure includes the material **42** in which a pattern is suitably formed, a thin layer **44** of a material which suitably forms a hard mask (for example, an SiO_2 layer), and any suitable photoresist layer **46** which responds to exposure and development. In a preferred embodiment, photoresist layer **46** is a negative tone photoresist (e.g. resist is substantially removed on development only in the substantially unexposed regions). In an alternative embodiment, a positive photoresist is used with an image reversal step to effectively utilize it as a negative tone material. In either case, a second optical exposure in the same photoresist level may be used to delimit the areas of the circuit over which the interferometric lithography pattern is defined, for example, to the core areas of a DRAM circuit.

With respect to FIG. **9B**, photoresist **46** is suitably exposed using interferometric lithography and suitably developed, thereby forming a periodic pattern **48** (at pitch p_{min}) in photoresist **46**. In a preferred embodiment, periodic pattern **48** comprises an array of lines at a substantially minimum pitch having a width substantially less than about $p_{min}/4$. With reference to FIG. **9C**, any suitable etching process preferably transfers periodic pattern **48** (the lines) into hard mask **44**. In a preferred embodiment, a very thin hard mask layer **44** is used such that the etching process does not have to be highly anisotropic. After etching, remaining photoresist **46** is suitably stripped.

Support for "first mask material"

-- and --

"parts of said first mask layer"

-- and --

"combined mask . . . "

With reference to FIG. 9D, a new photoresist layer **46** is suitably applied and structure **40** is suitably re-exposed and developed at substantially the same pitch, but with pattern **50** offset by $p_{min}/2$, thereby interpolating new lines **50** between (e.g. midway) previously defined lines **48** in hard mask **44**. With reference to FIG. 9E, any suitable etching process preferably transfers lines **50** into hard mask material **44**, thereby resulting in a pattern **48**, **50** with about one half the pitch of original structure **40**. Mathematically, this sequence of operations is represented as:

Support for "first mask material"

-- and --

"parts of said first mask layer"

-- and --

"combined mask . . . "

$$T(x) = \tau[E_1(x)] \times \tau[E_2(x)] \tag{7}$$

$$= \frac{a}{2}\left\{\sum_{n=-\infty}^{\infty}\left[\frac{\sin\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)}{\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)} e^{i\frac{4\pi n x \sin(\theta)}{\lambda}}\right] + \right.$$

$$\left.\sum_{n=-\infty}^{\infty}\left[\frac{\sin\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)}{\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)} e^{i\pi n} e^{i\frac{4\pi n x \sin(\theta_y)}{\lambda}}\right]\right\}$$

$$= \frac{a}{2}\left\{\sum_{n=-\infty}^{\infty}\left[\frac{\sin\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)}{\left(\frac{2\pi n a \sin(\theta)}{\lambda}\right)} e^{i\frac{8\pi n x \sin(\theta)}{\lambda}}\right]\right\}$$

where the factor of $e^{i\pi n}=(-1)^n$ in the second term arises because of the half-pitch shift of the second pattern. As a result, the even terms in the summations add, the odd terms cancel, and the final result is just the expression for a periodic square wave structure at twice the period [4 sin (θ)/l] of each exposure.

Support for "spatial frequencies"

With reference to FIGS. **10A–10F**, in an alternative embodiment, a similar process to FIGS. **9A–9E** (subtractive process with etching) is shown which similarly results in a factor of two multiplication of the pitch, except a positive tone photoresist is used in an additive process (deposition). Namely, photoresist layer **66** is preferably a positive tone photoresist (e.g. resist is substantially removed on development only in the substantially exposed regions). With reference to FIG. **10A**, a preferred exemplary structure includes the material in which a pattern is suitably formed **62** and any suitable positive tone photoresist layer **66**. With respect to FIG. **10B**, and **10C** positive photoresist **66** is suitably exposed using interferometric lithography and developed, thereby leaving positive photoresist **66** in a substantially periodic pattern **68** of a pitch of about p_{min}. In a preferred embodiment, periodic pattern **68** comprises an array of lines at a substantially minimum pitch having a width substantially less than about $p_{min}/4$.

With reference to FIG. **10C**, any suitable mask material **64** is preferably deposited substantially everywhere except in the region of positive photoresist **66**, then positive photoresist **66** is suitably stripped. With reference to FIG. **10D**, a new positive photoresist layer **66** is suitably applied and structure **60** is suitably re-exposed interferometrically and suitably developed at substantially the same pitch, but with pattern **70** offset by about $p_{min}/2$, thereby leaving photoresist **66** about midway between previously defined lines **68** in hard mask **64**. A second mask layer **72** is then suitably deposited substantially everywhere but in the region of remaining photoresist **66**, thereby serving as an etch mask to allow etching of etch mask **64**. With respect to FIG. **10E**, positive photoresist **66** is suitably stripped and, using mask layer **72** as an etch mask, lines **70** are suitably etched into mask **64**. With respect to FIG. **10F**, any suitable stripping process preferably removes second mask layer **72**, thereby resulting in a pattern **68**, **70** with about one half the pitch of original structure **60**. In a further alternative embodiment, the process of FIGS. **10A**–**10F** is suitably reversed by known image reversal techniques using positive tone resists.

The alignment between the two exposures described above (with respect to either FIGS. **9A**–**9E** or FIGS. **10A**–**10F**) can be accomplished by any suitable method. In a preferred embodiment, the alignment between the two exposures are suitably accomplished by the techniques described in U.S. Pat. No. 5,216,257—S. R. J. Brueck and Saleem H. Zaidi, Method and Apparatus for Alignment and Overlay of Submicron Lithographic Features (issued Jun. 1, 1993) and U.S. Pat. No. 5,343,292—S. R. J. Brueck and Saleem H. Zaidi, Method and Apparatus for Alignment of Submicron Lithographic Structures (issued Aug. 30, 1994), which are all herein incorporated by reference. In brief, the incident writing beams (or other longer wavelength, non-actinic beams) preferably impinge on the pattern resulting from the first exposure. The beams diffracted from the grating on the wafer surface are suitably caused to interfere with a standard interferometric optical system (mirrors and beamsplitters) and are preferably incident on an appropriate detector. The resulting projection moire fringe pattern is suitably used to set both the spatial frequency and the phase (offset) of the second exposure. In an alternative embodiment, a substantially similar process to the process described above for alignment of multiple interferometric lithography exposures is used to suitably align an interferometric lithography exposure to an optical lithography exposure.

An exemplary demonstration of subtractive spatial frequency doubling is shown in FIGS. **11A**–**11C**. In this exemplary embodiment, the starting material includes <110> Si (to allow anisotropic KOH etching as a final pattern transfer step) with a thin (~50-nm) Si_3N_4 sacrificial cap layer. This photoresist process uses image reversal with a 257-nm (doubled Ar-ion laser) source. FIG. **11A** shows an exemplary SEM after the first etch, as demonstrated in FIG. **10C**, with a pitch of approximately 260 nm. FIG. **11B** shows the exemplary results after the second etch, as demonstrated in FIG. **10F**, with the pitch suitably reduced to ~130 nm and the CD to ~60 nm. Finally, FIG. **11C** shows the exemplary results of an anisotropic KOH etch of 130-mm pitch pattern into the Si using the nitride layer as a hard mask. In FIG. **10C**, some etching of the sidewalls has occurred in the KOH etch step resulting in thinner lines and a smaller line:space ratio, namely the final Si linewidth is as small as about 20–40 nm.

In a preferred embodiment, this multiple exposure technique (as disclosed above with respect to FIGS. **9A**–**9E** and FIGS. **10A**–**10F**) is suitably repeated a number of times with appropriate offsets to produce pitches of about p/N where N=1 (original pattern), 2 (one additional exposure and processing sequence), 3 (two additional exposures and processing sequences), etc.

In an alternative embodiment, this technique can be extended to two-dimensional patterning by using either multiple exposures and/or multiple-beam single exposures. For a grid of holes or posts with equal pitches, p_1, in both the x- and y-directions, a second exposure at the same pitch but shifted by $p_{,1}/2$ in x and $p_1/2$ in y decreases the pitch (now p_2) to approximately $p_2=p_1/\sqrt{2}$. With two further exposures a new pitch (now p_3) of approximately $p_3=p_1/2$ is achieved. As discussed above, nonlinearities allow the extension of optics beyond the linear systems limit. As such, higher spatial frequencies can be accessed by taking advantage of nonlinearities in processing. In other words, the linear systems constraints apply to pattern frequencies, not to linewidths. This is dramatically illustrated by the micrograph in FIG. **11**D that shows a 50-nm CD line on a 2-μm pitch, a line:space ratio of 1:20. The very high spatial frequencies corresponding to this narrow line are the result of photoresist process nonlinearities, the exposure aerial image was a 2-μm period sine wave. Importantly, the process latitude for printing this fine line was much greater than that for printing the 150-nm dense line:space pattern. This is a superior result in that it is always more difficult to print 1:1 patterns since these occur very near the threshold dose for developing all the way through the resist. Larger line:space ratios are closer to saturation where the process is very forgiving of small dose variations and the nonlinearities (vertical sidewalls) are larger. Thus, it is easier (greater process latitude) to print smaller CD structures at a fixed pitch.

FIG. **11**E shows a concept drawing of how the aforementioned frequency doubling technique might be applied to a circuit pattern, in this case a typical SRAM pattern. The two colors indicate the patterns written in each exposure. No two features of the same color approach each other by less than 1.5 CD. The spacing is less than 2 CD because of the staggered features in the SRAM pattern, so changing the design to a CD grid would allow a straightforward doubling of the pattern density.

Support for “high spatial frequencies”

As shown below in FIGS. **12**–**17**, the present multiple exposure technique substantially uniformly produces structures with a linewidth less than the pitch and substantially accurately aligns the two exposures, so the present invention increases N.

In accordance with a preferred embodiment, for larger pitches, structures with linewidths a factor of 40 less than the pitch have been produced. With respect to FIG. **12**, a 0.05-μm wide photoresist line on a 2-μm pitch with a line:space ratio of 1:40 is shown. This experiment used a positive tone photoresist in accordance with FIGS. **9**A–**9**F; however, the process could be reversed with a negative tone resist or by known image reversal techniques using positive tone resists.

With respect to FIG. **14**, an example of a dense array of 90-nm diameter holes defined in a photoresist layer on a 180-nm pitch is shown. This pattern is suitably written in a double exposure process with two two-beam grating exposures and the wafer rotated by 90° between exposures. With respect to FIG. **15**, another example of a dense, hexagonal close packed pattern written with three two-beam exposures and the wafer rotated 120° between exposures is shown.

Multiple (greater than two) beam exposures suitably include another degree of freedom. With respect to FIG. **16**, an exemplary 2-D hole pattern suitably written with a five-beam geometry in a single exposure is shown. In a preferred embodiment, the multiple beam exposures suitably create more complex features, with correspondingly enhanced surface area. With respect to FIG. **17**, an exemplary calculation is shown with the structures obtained with the five-beam geometry of FIG. **16** when the exposure flux is increased to form an array of posts rather than the array of holes. As seen in FIG. **17**, the posts are substantially hollow cylindrical forms (donuts) having both inner and outer surfaces, thereby approximately doubling the perimeter when compared with the simple hole arrays of FIG. **16**. The approximate doubling of the perimeter in FIG. **17** leads to further enhanced surface area when suitably etching these structures into the polysilicon contact material. Compared to the one dimensional structures, two-dimensional features typically experience comparable or even greater surface area enhancements. Furthermore, with two-dimensional structures, the impact of a defect (e.g. too thin of a wall that collapses) is suitably lowered.

In addition to DRAM capacitors, multiplying the spatial frequency of lithographically defined structures suitably allows for substantial improvements in, inter alia, crystal growth, quantum structure growth and fabrication, flux pinning sites for high-T_c superconductors, form birefringent materials, reflective optical coatings, photonic bandgap, electronics, optical/magnetic storage media, arrays of field emitters and in other applications requiring large areas of nm-scale features.

More particularly, in another preferred embodiment, the present invention is suitably applied to textured substrates for crystal growth. An array of small scale structures is suitably fabricated as the epitaxial growth surface ("bed of nanoneedles"). At the initiation of growth, small islands of growth rather than the monolithic substrates are preferably used. This approach typically has advantages for growth of strained materials where the epitaxial film has a significantly different lattice constant than does the substrate material. For this "bed of nanoneedles" approach, edge effects and strain relaxation suitably provide advantages over monolithic growth.

Application of the present invention to quantum structure growth and fabrication is similar to the above crystal growth application with the exception that the growth typically involves at least two materials: a lower bandgap material surrounded by a higher bandgap material to provide a quantum wire or a quantum dot. The present invention suitably further reduces the dimensionality of quantum wells from 2-D sheets to 1-D wires and 0-D boxes by uniformly defining nucleation sites.

With respect to flux pinning sites for high-T_c superconductors, the present fabrication technique suitably provides flux pinning sites by inducing localized defects in the film to trap the flux lines. In order to achieve the desired critical currents, the density of trap sites is preferably on the nm-scale (~5–50 nm spacings). To induce these defects, the film is preferably denatured using a lithographic step after growth. Alternatively, defects are preferably induced in the crystal substrate before film growth because there is less risk of destroying the superconducting properties of the film.

The present invention suitably provides periodic structures, such as gratings, which preferably play a very important role in optics. The periodicities produced by the present invention are preferably shorter than the optical wavelength such that the improved periodicities give rise to significant modifications in both the linear and nonlinear optical response of materials. For example, the resulting one-dimensional gratings with pitches much less than the wavelength preferably result in a birefringent response such that the reflectivity and transmission differs between light polarized along the grating and light polarized perpendicular to the grating. Since the pitch is less than the wavelength, there are no diffracted orders from such a grating, implying high efficiency. This is known as form birefringence and offers the potential for a wide range of optical components.

Reflective optical coatings, known as Bragg reflectors, often consist of layered stacks of different materials with each layer having a ¼ wave optical thickness. Very high reflectivities are preferably achieved, even with relatively small refractive index differences between the materials. The extension to a periodic three dimensional optical structure is known as a photonic crystal. In the same way as semiconductor crystals have forbidden energy gaps within which electrons cannot exist, photonic crystals exhibit photonic bandgaps where specific wavelength bands of light cannot penetrate. The present invention provides a technique for large-scale manufacturing of the nano-scale two-dimensional patterns required for manufacturing photonic crystals for the infrared, visible and ultraviolet spectral regions. Further, using the present invention, defects may be suitably formed in this structure which give rise to important classes of optical emitters with unique properties such as thresholdless lasers.

The present invention is also preferably used to increase the number of transistors on semiconductor electronics, thereby allowing more and more smaller and smaller devices.

With respect to optical/magnetic storage media, the present invention defines individual nm-scale single-domain sites which preferably improve the storage density by reducing interactions between the information stored on individual sites. Moreover, by lithographically defining features on the media in accordance with the present invention, the tracking electronics preferably resolves smaller distances.

With respect to arrays of field emitters, as discussed above for quantum structures, for all of these techniques there can be a significant advantage in terms of feature and current density to starting with a higher resolution lithographic technique. The present invention also suitably simplifies the fabrication process by defining the initial structures in the nm range rather than the μm range.

While the present invention has been described in conjunction with the preferred and alternate embodiments set forth in the drawing figures and the specification, it will be appreciated that the invention is not so limited. For example, the method and apparatus for multiplying spatial frequency can also be used for other semiconductor-manufacturing related applications including test-structures for the development of next generation processing tools, flat-panel displays and any other application which requires low-cost, large-area, nm-scale patterning capability. Various modifications in the selection and arrangement of components and materials may be made without departing from the spirit and scope of invention as set forth in the appended claims.

We claim:

1. A method for obtaining a pattern wherein the Fourier transform of said pattern contains high spatial frequencies by combining nonlinear functions of intensity of at least two exposures combined with at least one nonlinear processing step intermediate between the two exposures to form three dimensional patterns comprising the steps of:

coating a substrate with a first photoresist layer;

exposing said first photoresist layer with a first exposure;

developing said first photoresist layer to form a first pattern in said first photoresist layer, said first pattern containing spatial frequencies greater than those in a two dimensional optical intensity image imposed onto said photoresist layer in said first exposure as a result of a nonlinear response of said first photoresist layer;

coating said substrate with a second photoresist layer;

exposing said second photoresist layer with a second exposure;

developing said second photoresist layer to form a second pattern in said second photoresist layer, said second pattern containing spatial frequencies greater than those in a two dimensional optical intensity image imposed onto said photoresist layer in said second exposure as a result of a nonlinear response of said second photoresist layer;

combining said patterns to provide a final pattern.

2. The method of claim **1** wherein said first exposure includes a plurality of exposures forming a plurality of images.

3. The method of claim **1** wherein said second exposure includes a plurality of exposures forming a plurality of images.

4. The method of claim **1**, wherein a minimum of said spatial frequencies along at least one direction in said first or second pattern is smaller than $2/\lambda$.

5. The method of claim **1**, wherein said intermediate nonlinear processing step enables a frequency distribution of said pattern which is altered from frequency distributions of only said first and said second exposure.

6. A method for obtaining a pattern wherein the Fourier transform of said pattern contains high spatial frequencies by combining nonlinear functions of intensity of at least two exposures combined with at least one nonlinear processing step intermediate between the two exposures to form three dimensional patterns comprising the steps of:

coating a substrate with a first mask material and a first photoresist layer;

exposing said first photoresist layer with a first exposure

developing said photoresist to form a first pattern in said first photoresist layer, said first pattern containing spatial frequencies greater than those in a two dimensional optical intensity image imposed onto said photoresist layer in said first exposure as a result of a nonlinear response of said first photoresist layer;

transferring said first pattern into said first mask material, said first mask material comprising at least one of SiO_2, Si_3N_4, a metal, a polysilicon and a polymer;

coating said substrate with a second photoresist;

exposing said second photoresist with a second exposure

developing said second photoresist layer to form a second pattern in said second photoresist layer, said second pattern containing spatial frequencies greater than those in a two dimensional optical intensity image imposed onto said photoresist layer in said second exposure as a result of a nonlinear response of said second photoresist layer;

transferring said first pattern and said second pattern into said substrate using a combined mask including parts of said first mask layer and said second photoresist;

removing said first mask material and said second photoresist.

7. The method of claim **6** wherein said transferring step includes at least one of etching, deposition and-lift off, and damascene.

8. A method for increasing spatial frequency content of lithographic patterns comprising the steps of:

depositing a material;

depositing a photoresist on said material;

exposing a periodic image in said photoresist, said periodic image having a pitch p_{min} and a linewidth less than $p_{min}/2$;

developing said periodic image to form a periodic pattern in said photoresist;

transferring said periodic pattern to said material;

depositing a second photoresist layer on said material;

offsetting said periodic pattern by $p_{min}/2$;

repeating said exposing, developing and transferring steps, thereby interpolating new said pattern midway between said pattern.

9. The method of claim **8**, wherein said step of depositing a material includes depositing doped polysilicon.

10. The method of claim **8**, wherein said material includes an SiO_2 overlayer configured to act as a hardmask during said etching step.

11. The method of claim **8**, wherein said step of depositing a photoresist includes depositing at least one of a negative photoresist, a positive photoresist and a positive photoresist with an image reversal step.

12. The method of claim **8**, wherein said step of exposing a photoresist includes exposing using interference lithography.

13. The method of claim **8**, wherein said step of exposing a photoresist includes exposing using interference lithography in combination with another lithographic technique.

14. The method of claim **8**, wherein said step of exposing a photoresist includes exposing using interference lithography in combination with an optical stepper.

15. The method of claim **8**, wherein said step of exposing a photoresist includes image reversal.

16. The method of claim **8**, wherein said step of developing said periodic pattern includes etching said pattern into a hardmask.

17. The method of claim **8**, wherein said exposing step includes exposing with at least one of multiple exposures and multiple-beam single exposures.

18. The method of claim **8**, wherein said step of depositing a material includes depositing a material on at least one of a textured substrate, a quantum structure, a flux pinning site for high-T_c superconductors, a birefringent material, a reflective optical coating, a photonic bandgap, an electronic device, an optical storage media, a magnetic storage media, an array of field emitters and a Dynamic Random Access Memory capacitor.

19. A method for multiplying the spatial frequency content of a one-dimensional line/space pattern consisting of the steps of:

providing a substrate;

depositing a material on said substrate;

depositing a photoresist on said material;

exposing and developing a periodic pattern in said photoresist, said periodic pattern having a pitch p_{min} and a linewidth less than $p_{min}/2$;

transferring said periodic pattern into said material by a process step;

removing said first photoresist layer;

depositing a second photoresist layer;

exposing said second photoresist layer with said periodic pattern offset by $p_{min}/2$;

repeating the exposing, developing and transferring steps N times with offsets of p_{min}/N, thereby interpolating N new said patterns equally spaced midway between said pattern,

etching exposed said material down to a predetermined depth, thereby transferring said pattern through said material;

transferring said pattern into said substrate.

20. The method of claim **19**, wherein said step of depositing a material includes depositing in-situ doped polysilicon.

21. The method of claim **19**, wherein said material includes an SiO_2 overlayer configured to act as a hardmask during said etching step.

22. The method of claim **19**, wherein said step of depositing a photoresist includes depositing at least one of a negative photoresist, a positive photoresist and a positive photoresist with an image reversal step.

23. The method of claim **19**, wherein said step of exposing a photoresist includes exposing using interference lithography.

24. The method of claim **19**, wherein said step of exposing a photoresist includes exposing using interference lithography in combination with a lithographic technique.

25. The method of claim **19**, wherein said step of exposing a photoresist includes exposing using interference lithography in combination with an optical stepper.

26. The method of claim **19**, wherein said step of exposing a photoresist includes image reversal.

27. The method of claim **19**, wherein said step of developing said periodic pattern includes etching said pattern into a hardmask.

28. The method of claim **19,** further comprising at least one of multiple exposures and multiple-beam single exposures.

29. The method of claim **19,** wherein said pattern size avoids overlapping of pattern features upon doubling of said frequency.

30. The method of claim **19,** further comprising registering said periodic pattern to a contact patterning.

31. The method of claim **19** further comprising the step of allowing about 100 nm between adjacent said patterns.

32. The method of claim **19,** wherein said step of depositing a material includes depositing an NO layer.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,042,998 Page 1 of 1
APPLICATION NO. : 08/932428
DATED : March 28, 2000
INVENTOR(S) : Steven R. J. Brueck et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In column 1, after the title and “RELATED APPLICATIONS,” please insert the following paragraph:

-- This application is a continuation-in-part of U.S. Patent Application No. 08/490,101 filed June 6, 1995, which has matured into U.S. Patent No. 5,705,321, which is a continuation of U.S. Patent Application No. 08/123,543 filed September 20, 1993 and now abandoned. --

Signed and Sealed this

Thirtieth Day of December, 2008

Jon W. Dudas

JON W. DUDAS
Director of the United States Patent and Trademark Office