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(71) Applicant: LSI LOGIC CORPORATION [US/US]; 1551 McCarthy Boulevard, Patent Law Dept., M/S: D–106, Milpitas, CA 95035 (US).

(72) Inventors: MEDVEDEVA, Marina, G.; Projezd Donela-jtisa 12, Corp. 1, Quart. 66, Moscow, 123373 (RU). SCEPANOVIC, Ranko; 1063 Avondale Street, San Jose, CA 95129 (US). PETRANOVIC, Dusan; 7970–1 McClel-lan Road, Cupertino, CA 95014 (US).

(74) Agent: PURSEL, David, G.; LSI Logic Corporation, 1551 McCarthy Boulevard, Patent Dept., M/S: D–106, Milpitas, CA 95035 (US).

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(54) Title: HYBRID AERIAL IMAGE SIMULATION

(57) Abstract

An aerial image produced by a mask having transmissive portions is simulated by dividing the transmissive portions of the mask into primitive elements and obtaining a spatial frequency function corresponding to each of the primitive elements. The spatial frequency functions corresponding to the primitive elements are combined to obtain a transformed mask transmission function, and the transformed mask transmission function is utilized to generate a simulation of the aerial image.

HYBRID AERIAL IMAGE SIMULATION

BACKGROUND OF THE INVENTION

5   Field of the Invention

The present invention relates to simulation of an aerial image, and particularly relates to simulation of an aerial image produced by a mask to be used in patterning an integrated circuit (IC) chip during semiconductor wafer fabrication.

10   Description of the Related Art

A.   Wafer Construction.

Photolithography is a common technique employed in the manufacture of semiconductor devices. Typically, a semiconductor wafer is coated with a layer
15   (film) of light-sensitive material, such as photoresist. Using a patterned mask or reticle, the wafer is exposed to projected light, typically actinic light, which manifests a photochemical effect on the photoresist, which is subsequently chemically etched, leaving a pattern of photoresist "lines" on the wafer corresponding to the pattern on the mask.

20   A "wafer" is a thin piece of semiconductor material from which semiconductor chips are made. The four basic operations utilized to fabricate wafers include (1) layering, (2) patterning, (3) doping and (4) heat treatments.

The layering operation adds thin layers of material, including insulators, semiconductors, and conductors, to a wafer surface. During the layering operation,
25   layers are either grown or deposited. Oxidation involves growing a silicon dioxide (an insulator) layer on a silicon wafer. Deposition techniques include, for example, chemical vapor deposition, evaporation, and sputtering. Semiconductors are generally deposited by chemical vapor deposition, while conductors are generally deposited with evaporation or sputtering.

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Patterning involves the removal of selected portions of surface layers. After material is removed, the wafer surface has a pattern. The material removed may form a hole or an island. The process of patterning is also known to those skilled in the relevant art as microlithography, photolithography, photomasking and

5   masking. The patterning operation serves to create parts of the semiconductor device on the wafer surface in the dimensions required by the circuit design and to locate the parts in their proper location on the wafer surface.

Doping involves implanting dopants in the surface of the wafer through openings in the layers to create the n-type and p-type pockets needed to form the

10   N-P junctions for operation of discrete elements such as transistors and diodes. Doping is generally achieved with thermal diffusion (the wafer is heated and exposed to the desired dopant) and ion implantation (dopant atoms are ionized, accelerated to high velocities and implanted into the wafer surface).

Construction of semiconductor wafers with these steps is well known

15   in the art of semiconductor fabrication. Examples of wafer construction processes are described in United States Letter Patent No. 5,679,598 issued to Yee on October 21, 1997, entitled "Method of Making a CMOS Dynamic Random-Access Memory (DRAM)," United States Letter Patent No. 5,663,076 issued to Rostoker et al. on September 2, 1997, entitled "Automating Photolithography in the Fabrication of

20   Integrated Circuits," United States Letter Patent No. 5,595,861 issued to Garza on January 21, 1997, entitled "Method of Selecting and Applying a Top Antireflective Coating of a Partially Fluorinated Compound," United States Letter Patent No. 5,444,265 issued to Hamilton on August 22, 1995, entitled "Method and Apparatus for Detecting Defective Semiconductor Wafers During Fabrication Thereof," and

25   United States Letter Patent No. 4,652,134 issued to Pasch et al. on March 24, 1987, entitled "Mask Alignment System." The specifications of these five patents identified in this paragraph are hereby incorporated herein as though set forth in full by this reference.

B.   Patterning And Proximity Effects.

One of the most critical operations in wafer fabrication, patterning sets the dimensions of the electronic devices to be implemented on the IC chip. Errors in the patterning process can cause distortions that cause changes in the functions
5   of these electronic devices.

Design rule limitations frequently are referred to as critical dimensions. A critical dimension of a circuit is commonly defined as the smallest width of a line or the smallest space between two lines. Consequently, the critical dimension determines the overall size and density of an IC. In present IC technology, the
10   smallest critical dimension for state-of-the-art circuits is 0.3 micron for line widths and spacings.

Once the layout of the circuit has been created, the next step to manufacturing the integrated circuit is to transfer the layout onto a semiconductor substrate. Photolithography is a well known process for transferring geometric
15   shapes present on a mask onto the surface of a silicon wafer. In the field of IC lithographic processing, a photosensitive polymer film called photoresist is normally applied to a silicon substrate wafer and then allowed to dry. An exposure tool is utilized to expose the wafer with the proper geometrical patterns through a mask (or reticle) by means of a source of light or radiation. After exposure, the wafer is
20   treated to develop the mask images transferred to the photosensitive material. These masking patterns are then used to create the device features of the circuit.

Figure 1A is a functional block diagram illustrating a system for patterning an IC chip 26 using a mask 22. Referring to Figure 1, light 21 is incident on mask 22 at a right angle. Such would be the case for a single point light source
25   directly above mask 22 and far enough from mask 22 so that the wavefront at mask 22 would be approximately planar. It should, however, be noted that light 21 is shown in this manner for illustration purposes only. Generally, the light source will be an extended body consisting of many different points and, accordingly, light generally will strike mask 22 at many different angles. Thus, as shown in Figure 1B,
30   the light from points 31 and 32 on light source 30 will strike mask 35 at different angles.

Mask 22 includes transmissive and non-transmissive portions which effectively transmit and block light 21 so as to produce the desired pattern on IC chip 26. The light 23 exiting from mask 22 passes through optical system 24 and, finally, contacts IC chip 26, forming a light intensity pattern. Often, optical system 24 merely

5   comprises the distance between mask 22 and IC chip 26. However, optical system 24 may include one or more lenses, mirrors and/or other optical elements.

An important limiting characteristic of the exposure tool is its resolution value. The resolution for an exposure tool is defined as the minimum feature that the exposure tool can repeatedly expose onto the wafer. Currently, the resolution

10   for most advanced optical exposure tools is around 0.2 micron. Thus, the resolution value of present lithographic equipment is close to the critical dimension for most IC circuit designs. Consequently, the resolution of the exposure tool may influence the final size and density of the IC circuit. As the critical dimensions of the layout become smaller and approach the resolution value of the lithographic equipment, the

15   consistency between the masked and actual layout pattern developed in the photoresist is significantly reduced. Specifically, it is observed that differences in pattern development of circuit features depends upon the proximity of the features to one another.

The magnitude of such proximity effects depends on the proximity or

20   closeness of the two features present on the masking pattern. Proximity effects are known to result from optical diffraction in the projection system. This diffraction causes adjacent features to interact with one another in such a way as to produce pattern-dependent variations.

Proximity effects and methods for correcting for them (i.e., optical

25   proximity correction, or OPC, methods) are discussed in United States Letters Patent No. 5,682,323 issued on October 28, 1997, to Pasch et al. entitled "System and Method for Performing Optical Proximity Correction on Macrocell Libraries" (hereinafter the "Pasch '323 patent"). The specification of the Pasch '323 patent is incorporated herein as though set forth in full by this reference. The system and

30   method described in the Pasch '323 patent performs optical proximity correction on an integrated circuit mask design by initially performing optical proximity correction

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on a library of cells that are used to create the IC. The pre-tested cells are imported onto a mask design. All cells are placed a minimum distance apart to ensure that no proximity effects will occur between elements fully integrated in different cells. An optical proximity correction technique is performed on the mask design by

5   performing proximity correction only on those components, e.g., lines, that are not fully integrated within one cell.

Proximity effects and methods for correcting for them are also discussed in United States Letters Patent No. 5,705,301 issued on January 6, 1998, to Garza et al. entitled "Performing Optical Proximity Correction with the Aid of

10   Design Rule Checkers" (hereinafter the "Garza '301 patent"). The specification of the Garza '301 patent is incorporated herein as though set forth in full by this reference. The system described in the Garza '301 patent involves a method for identifying regions of an integrated circuit layout design where optical proximity correction will be most useful and then performing optical proximity correction on

15   those regions only.

More specifically, the method includes the following steps: (a) analyzing an integrated circuit layout design with a design rule checker to locate features of the integrated circuit layout design meeting predefined criteria; and (b) performing optical proximity correction on the features meeting the criteria in order

20   to generate a reticle design. The criteria employed by the design rule checker to select features include outside corners on patterns, inside corners on features, feature size, feature shape, and feature angles.

C.   Mask Design.

25   An overview of a technique for designing a mask will now be described with reference to the flow diagram shown in Figure 2. Referring to Figure 2, in step 42 an initial mask pattern is obtained. Generally, points in the initial mask pattern will have an amplitude of one where the pattern is supposed to appear on the chip and an amplitude of zero where no pattern is to appear on the chip. However, the initial

30   mask pattern instead may be specified in other ways.

In step 44, an aerial image which would be produced by a mask having the mask pattern is simulated. Examples of conventional techniques for simulating an aerial image are described below.

In step 46, it is determined whether the simulated image is acceptable. Generally, the main criterion in making this determination is whether the simulated image has sufficient resolution to enable patterning which will result in error-free device fabrication. If the image is acceptable, then processing proceeds to step 48 in order to fabricate a mask having the designed pattern. Otherwise, processing proceeds to step 52.

In step 52, the mask pattern is altered, such as by adding and/or modifying serifs, in an attempt to improve the resolution of the aerial image. Such a process is described in more detail below. Upon completion of mask pattern alteration, processing returns to step 44 in order to simulate an aerial image based on the new mask pattern.

D.   Proximity Effect Correction.

A technique related to proximity effects involves the use of modified shapes or adjacent subresolution geometries to improve imaging. An example of this is the use of serifs on the corners of contacts. For contacts with dimensions near the resolution limit of the optics, a square pattern on the reticle will print more nearly as a circle. Additional geometries on the corners will help to square the corners of the contract. Such techniques often are called proximity correction. An example of such a technique is described in U.S. Patent Application Serial No. 09/034,550 filed March 3, 1998 and titled "Method And Apparatus For Application Of Proximity Correction With Relative Segmentation," which application is incorporated by reference herein as though set forth herein in full.

Proximity effects are a well-known phenomenon in electron beam lithography, where they result from electron scattering. In optical lithography proximity effects are caused by the phenomenon of diffraction. As a consequence of proximity effects, printed features do not have simple relationships to reticle

dimensions.· This creates a situation in which it is difficult to fabricate a photomask where the designer gets what he or she wants on the wafer.

Some limited form of proximity correction has been in use for at least two or three decades. These pattern modifications were usually requested by a

5   wafer engineer based on knowledge of a particular process step. In recent years, proximity correction has become more of a science than an art due to the introduction of several proximity correction software programs. The proximity correction process consists of measuring several generic test patterns processed on a wafer and constructing a multilevel lookup table from the measured data.

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E.   Numerical Simulation of an Aerial Image

Lithographic simulators are becoming an important tool in the evaluation of optimal lithographic processing. Specifically, by simulating aerial images, the time required to design a mask often can be shortened. Simulators

15   often are also useful for correcting optical proximity effects.

The aerial image produced by a mask, or the light intensity in an optical projection system's image plane, is a critically important quantity in microlithography for governing how well a developed photoresist structure replicates a mask design. The aerial image represents, to a large extent, the optical information about the

20   mask that enters into the photoresist structure. Of course, the full calculation of the resist structure generally has to take into account other factors, such as propagation of light within the resist, exposure of the resist, any subsequent thermal or other such processes, and the dissolution of the resist. Nevertheless, the aerial image typically is the single most important predictor of mask printability.

25   The models used in conventional aerial image simulators are based either on scalar diffraction theory or vector diffraction theory. The models based on scalar theory usually follow the analysis of Hopkins. In Hopkins's analysis, light intensity is propagated through the optical system. The mask plane is treated as a partially coherent source surface, and a coherent transfer function describes how a

point source in the mask plane is imaged in the plane of the resist. The aerial image

(light intensity) at a point $\vec{r}_p$ is given as:

$$I(\vec{r}_p) = \int\int\int\int U(\vec{r}_{m1}) U^*(\vec{r}_{m2}) K(\vec{r}_{m1},\vec{r}_p) K(\vec{r}_{m2},\vec{r}_p) B(\vec{r}_{m1},\vec{r}_{m2}) d\vec{r}_{m1} d\vec{r}_{m2} \qquad (1)$$

where $\vec{r}_{m1}$ and $\vec{r}_{m2}$ are points in the mask plane; $K(\vec{r}_{m1},\vec{r}_p)$ is the coherent impulse

5   response function of the optical system; $U(\vec{r}_{m1})$ is the mask complex transmission

function; and $B(\vec{r}_{m1},\vec{r}_{m2})$ is the mutual coherence function of the light at the mask

plane.

If expression (1) is used for calculation of an aerial image at point $\vec{r}_p$,

the number of operations required generally is on the order of L^2, where L is the

10   number of points in the region of integration. It is noted that L generally determines

the accuracy of the numerical integration of the integral in equation (1). In order to

calculate the aerial image at a mesh with N nodes, the number of operations

required generally is on the order of NL^2. Frequently, L is of the same order as N.

The second group of models (i.e., those based on vector diffraction

15   theory) generally follow the work of Yeung, who traces vector electric fields through

the optical system onto the photoresist surface. Specifically, each ray emanates

from a particular source point and travels through a different portion of the mask and

the optical system. One advantage of this method is the possibility of application of

the Fast Fourier Transform (FFT) in the calculation of coherent images from each

20   source point. The electric field at the resist surface due to that source point can be

obtained by integration over the solid angles subtended by the optical system, and

may be represented as:

$$I(\vec{r}_p) = \frac{1}{I_0} \int\int d\vec{r}_u I(\vec{r}_u) \left| \int\int d\vec{\rho}\, F_c(\vec{\rho}) H(|\vec{\rho} + \sigma\vec{r}_u|) \exp\{i2\pi\vec{\partial}\vec{\rho}\vec{r}_p\} \right|^2 \qquad (2)$$

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where

$$F_L\left(\vec{\rho}\right) = \iint U\left(\vec{r}_m\right)\exp\left[-i2\pi c M\, \vec{r}_m \cdot \vec{\rho}\right] d\,\vec{r}_m \qquad (3)$$

is the Fourier transform of the mask transmission function, $H\left(\vec{\rho}\right)$ is the coherent

transmission function of the optical system, $I\left(\vec{r}_u\right)$ is the intensity distribution at the

5   source surface, and I_0 is the open frame intensity.

The aerial image calculation according to equation (2) thus consists of the following steps: (1) find the Fourier transform of the mask transmission function, which is called the spatial frequency spectrum of the mask; (2) multiply the spatial frequency spectrum of the mask by the coherent transmission function of the optical

10   system, and repeat this step for each source point used in the calculation of the aerial image; (3) find the inverse Fourier transform of the function obtained in step (2); (4) multiply the result obtained in step (3) by its complex conjugate value; and (5) sum the coherent aerial images from all source points.

Steps (1) and (3) may be executed with the FFT algorithm. This

15   calculation generally is the fastest way of obtaining the aerial image at a mesh having N nodes, because it typically only requires on the order of P(N+1)lgN operations, where P is the number of source points and typically is much smaller than N.

A variety of simulators are commercially available. Probably the most

20   popular is Fast Aerial Image Model (FAIM), developed by Vector Technologies, Inc. and Princeton University. FAIM is capable of simulating segments of a computer-aided design (CAD) layout. It is generally uniform in accuracy and enables the user to simulate an aerial image of a segment (4 x12 microns) in about 12 seconds on a 20 MFLOPS workstation.

25   As noted above, aerial image simulators are very important in OPC. In these applications, the simulator is required to be very fast because it is in a loop for performing an iterative correction procedure. Accordingly, improvements in the

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speed of such simulators are highly desirable, particularly when such simulators are used in OPC.

As noted above, Yeung's technique is relatively fast, because it can be executed using the FFT algorithm. However, Yeung's technique typically introduces
5   additional errors into the simulation process. Specifically, prior to determining the FFT in step (1) above, the mask transmission function generally must first be rasterized. In this regard, the mask transmission function typically is initially represented in GDS2 format, which provides a geometric description of the mask pattern. Transformation into raster format is accomplished by sampling the mask
10   pattern on a rectangular mesh. However, the mask transmission function generally is not analytical near polygon boundaries, and therefore the GDS2-to-raster transformation often introduces errors. In general, these areas become larger as the polygon dimensions become smaller.

An example of such errors is illustrated with reference to Figures 3A
15   and 3B. Specifically, Figure 3A illustrates a mask pattern 71 superimposed over a mesh 72. Mesh 72 includes regularly spaced nodes, such as nodes 74. Generally, rasterization is performed by determining whether a node is more or less than 50 percent occupied by transmissive portions of the mask pattern. If a particular node is more than 50 percent occupied by transmissive portions, the entire node is
20   represented as transmissive. Otherwise, the entire node is represented as non-transmissive. Thus, Figure 3B illustrates a patten 78 which results after rasterizing mask pattern 71. As seen by comparing Figures 3B and 3A, several errors have occurred during rasterization. In particular, pattern 78 is shifted to the left and upward as compared to pattern 74. In addition, the entire triangular portion 79 of
25   pattern 74 has been eliminated in pattern 78.

The effects of rasterization error can be reduced by using a finer rasterization mesh. However, using a finer mesh also significantly increases the complexity of the required calculations by increasing the number of required operations. Thus, the conventional techniques typically require a trade-off between
30   speed and accuracy.

What is needed, therefore, is a technique for aerial image simulation which can maintain high accuracy and which can be executed very quickly.

SUMMARY OF THE INVENTION

5   The present invention addresses the foregoing problems by dividing a mask pattern into primitive elements, obtaining a spatial frequency function for each primitive element, and then combing those functions to obtain a transformed mask transmission function which can be used to simulate the aerial image produced by the mask.

10   Thus, according to one aspect, the invention simulates an aerial image produced by a mask having transmissive portions by dividing the transmissive portions of the mask into primitive elements and obtaining a spatial frequency function corresponding to each of the primitive elements. The spatial frequency functions corresponding to the primitive elements are combined to obtain a

15   transformed mask transmission function, and the transformed mask transmission function is utilized to generate a simulation of the aerial image.

According to a further aspect, the invention simulates an aerial image produced by a mask having transmissive portions by dividing the transmissive portions of the mask into primitive elements and obtaining a spatial frequency

20   function corresponding to each of the primitive elements. Te spatial frequency functions corresponding to the primitive elements are combined to obtain a transformed mask transmission function, and the aerial image is simulated by combining the transformed mask transmission function with an optical system coherent transmission function and performing an inverse spatial frequency

25   transformation. It is a further feature of this aspect of the invention that at least two of the primitive elements have different shapes.

By virtue of the foregoing arrangements, the present invention generally can avoid many of the problems associated with conventional simulation techniques. For example, rasterization errors which are present in many

30   conventional techniques can be largely eliminated. In addition, a relatively coarse

FFT mesh often can be utilized, increasing computation speed while still maintaining good accuracy.

A more particularized aspect of the present invention includes using primitive elements for which a spatial frequency transformation can be determined

5   analytically. Other particularized aspects include modifying the mask based on the simulated aerial image by adding correction elements to the mask, and then determining a new transformed mask transmission function by combining spatial frequency functions corresponding to the added correction elements with the previously obtained transformed mask transmission function. This latter aspect of

10   the invention often permits relatively easy calculation of the effects of adding or replacing correction elements on the resulting aerial image. In addition, because simulation accuracy generally is unrelated to mask feature size in the present technique, it is usually possible to calculate the effects of small correction elements, i.e., having dimensions much smaller than the resolution of the optical system.

15   The foregoing summary is intended merely to provide a quick understanding of the general nature of the invention. A more complete understanding of the invention can be obtained by referring to the claims and the following detailed description of the preferred embodiments in connection with the accompanying figures.

20

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A and 1B are functional block diagrams illustrating IC chip patterning.

Figure 2 is a flow diagram for explaining how to design a mask

25   transmission function.

Figures 3A and 3B illustrate a conventional technique for simulating an aerial image.

Figure 4 is a flow diagram for explaining geometric aerial image simulation according to a preferred embodiment of the invention.

Figure 5 is a flow diagram for explaining mask pattern decomposition according to a representative embodiment of the invention.

Figures 6A and 6B illustrate examples of mask pattern decomposition using the method shown in Figure 5.

5   Figure 7 illustrates how to determine an optical system response to a right triangular primitive element according to the preferred embodiment of the invention.

Figure 8 is a flow diagram for explaining hybrid aerial image simulation according to a preferred embodiment of the invention.

10   Figures 9A and 9B illustrate a rectangular primitive element and a triangular primitive element, respectively.

Figure 10 illustrates a block diagram of a general purpose computer which is one suitable platform for implementing the methods of the present invention.

15   DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The following describes aerial image simulation techniques according to the present invention. Any of the following techniques may be utilized in mask design, such as to simulate an aerial image in step 44, as shown in Figure 2.

20   A.   Geometric Aerial Image Simulation.

An embodiment of a geometric aerial image simulation technique according to the present invention will now be described with reference to the flow diagram shown in Figure 4. Briefly, according to Figure 4, mask data are input; the transmissive portions of the mask are divided into primitive elements; an optical

25   system response is obtained for each primitive element, for a single coherent light source point; the responses over all primitive elements are combined to obtain an overall mask response; and finally, the light intensity is determined at the image place by combining responses over all light source points.

In more detail in step 92, mask data are input. Typically the mask data

30   will be in GDS2 format and will specify the transmissive portions of the mask pattern.

In step 94, the transmissive portions of the mesh are divided into primitive elements. In the preferred embodiment of the invention, each polygon in the mask pattern is processed separately, as described in more detail below. In this regard, the processed polygons can be the polygons as they naturally occur in the

5   mask pattern. In addition, polygons can result from dividing the mask into a number of windows (such as rectangular windows), which division may be performed, for example, in order to facilitate parallel processing. As a result of such division, a single polygon can be divided into two or more polygons, and those smaller polygons can be processed separately. However, it should be noted that in order to perform

10   parallel processing, the techniques of the present invention generally will not require spatial division of the mask area. That is, separate polygons ordinarily can be processed independently using the techniques of the present invention, regardless of their relative spatial positions.

Preferably, the primitive elements are rectangles and right triangles.

15   However, the invention is not so limited, and the primitive elements may include other geometric shapes in addition to or instead of rectangles and right triangles. For example, as noted below, the primitive elements may include polygons which can be formed as the sum of rectangles. It is also preferred that step 94 is performed by systematically making cuts in the mask pattern to divide the pattern

20   into such primitive elements.

One example of such a technique will now be described with reference to the flow diagram shown in Figure 5. Specifically, Figure 5 illustrates a flow diagram for explaining segmentation of a single polygon in the mask pattern according to a representative embodiment of the invention. The steps shown in

25   Figure 5 are repeated for each polygon in the mask pattern. It is noted that most polygons will consist mainly of horizontal and vertical edges, but may also consist of edges oriented at arbitrary angles. Because most of the edges are either horizontal or vertical, the method shown in Figure 5 divides a polygon into rectangular and right triangle primitives by making horizontal and vertical cuts in the

30   polygon.

Briefly, according to Figure 5, the first vertex in the current polygon is selected; if the current vertex is an inner angle and is a horizontal/vertical vertex, then one of the edges forming the vertex is continued to form a cut; if the vertex is not a horizontal/vertical vertex, then a horizontal or vertical cut is made in the

5   polygon; the foregoing steps are then repeated for each vertex while traversing the polygon in a single direction (e.g., clockwise or counter-clockwise); all of the foregoing steps are then repeated for each polygon in the mask pattern.

In more detail, in step 122, the first vertex of the current polygon is selected.   In the current embodiment, the initial vertex is selected arbitrarily.

10   However, the invention also contemplates selecting the initial vertex according to pre-defined rules in order to optimize segmentation of the polygon.

In step 124, it is determined whether the current vertex is: (1) an inner angle and (2) a horizontal/vertical vertex. With regard to (1), the vertex is an "inner angle" if continuing either edge at the vertex would extend the edge into the polygon.

15   With regard to (2), the vertex is a "horizontal/vertical" vertex if one of the edges is horizontal and the other is vertical. As noted above, the horizontal and vertical orientations will have been decided in advance based on the predominant orientations of the edges in the mask pattern. If both of conditions (1) and (2) are true, then processing proceeds to step 126. Otherwise, processing proceeds to step

20   128.

In step 126, one of the horizontal and vertical edges is continued at the vertex into the polygon until either another edge or a cut is encountered. In the present embodiment, the edge to be continued is selected arbitrarily. However, the present invention also contemplates selecting the specific edge according to pre-

25   defined rules directed at optimizing polygon segmentation.

In step 128, it is determined whether the current vertex is a non-horizontal/vertical vertex, i.e., if one of the edges is neither horizontal nor vertical. If the current vertex is a non-horizontal vertex, then processing proceeds to step 130. Otherwise processing proceeds to step 132.

In step 130, a horizontal or vertical cut is made into the polygon at the current vertex. This cut is preferably made as follows. If one of the edges is either horizontal or vertical, then (1) the edge is extended into the polygon if it can be so extended, or (2) a cut oriented 90 degrees relative to such horizontal or vertical edge

5   is made into the polygon if such vertical or horizontal edge cannot be extended into the polygon. If neither edge is horizontal or vertical, then a horizontal or vertical cut is made at the vertex with the specific direction being selected arbitrarily. In any case, the cut is made into the polygon until either another edge or a cut is encountered. It is noted that while the foregoing technique for performing step 130

10   is preferred, other techniques may instead be used.

In step 132, it is determined whether the current vertex is the last vertex. If it is, then the current polygon is completed and the next polygon is selected. Otherwise, processing proceeds to stepo134.

In step 134, the next vertex is selected, preferably vertexes are

15   selected for the current polygon by traversing around the polygon in a consistent direction, such as consistently in a clockwise or consistently in a counter-clockwise direction. Upon completion of step 134, processing proceeds to step 124 to begin analyzing the new vertex to determine whether any cut should be made at that vertex.

20   Although the foregoing describes one technique for segmenting polygons into primitive elements, the invention is not limited only to the above-described technique. Rather, any technique may be used for segmentation of the mask pattern. In particular, the specific technique chosen may depend upon the types of primitive elements to be used.

25   Examples of the foregoing method will now be given with reference to Figures 6A and 6B. Figure 6A illustrates a polygon 160 which includes vertices 161 to 166. In the present example, polygon 160 is segmented by beginning at vertex 161 and proceeding in a clockwise direction. Vertex 161 is a horizontal/vertical vertex. However, vertex 161 is not an inner angle because neither of edges 181 or

30   182, if extended at vertex 161, would extend into polygon 160. Accordingly, no cut

is made at vertex 161. The next vertex is vertex 162, which is also a horizontal/vertical vertex, but which is not an inner angle.

Next, vertex 163 is a non-horizontal/vertical vertex because edge 184 is neither horizontal nor vertical. Vertical edge 183 cannot be extended into polygon 160 at vertex 163. Accordingly, a cut 172 is made at vertex 163 with cut 172 being orthogonal to edge 183. Cut 172 continues into polygon 160 until edge 181 is encountered.

Next, vertex 164 is also a non-horizontal/vertical vertex because edge 184 is neither horizontal nor vertical. Because edge 185 is vertical and can be extended into polygon 160, a cut 174 is made into polygon 160 which extends from edge 185 and continues into polygon 160 until cut 172 is encountered.

Each of vertices 165 and 166 is a horizontal/vertical vertex, but is not an inner vertex. Accordingly, no cuts are made at those vertices. At this point, the segmentation of polygon 160 is completed. As can be seen in Figure 6A, three primitive elements have been identified; rectangles 191 and 192 and right triangle 193.

The next example concerns polygon 200 shown in Figure 6B. Segmentation begins with vertex 201 and proceeds in a clockwise direction.

Each of vertices 201 and 202 is a horizontal/vertical vertex, but is not an inner angle. Accordingly, no cuts are made at those vertices.

Vertex 203 is a horizontal/vertical vertex. In addition, vertex 203 is an inner angle because either edge 223 or edge 224 can be extended into polygon 200. As noted above, in the current embodiment, the edge to be extended is determined arbitrarily. In the current example, edge 223 is selected because it is the first edge encountered in a clockwise direction. Accordingly, cut 241 is made by extending edge 223 into polygon 200 until edge 230 is encountered.

Next, vertex 204 is also a horizontal/vertical vertex and is an inner angle. Accordingly, edge 224 (the first encountered in a clockwise direction) is extended into polygon 200 to form cut 242, which continues until edge 227 is encountered.

Next, vertices 205, 206, 207 and 208 are all horizontal/vertical vertices, but are not inner angles. Accordingly, no cut is made at those vertices.

Next, vertex 209 is a horizontal/vertical vertex and is an inner angle. Accordingly, edge 229 (which is the first encountered in a clockwise direction) is

5   extended into polygon 200 to form cut 243, which continues until encountering edge 224.

Next, vertex 210 is a non-horizontal/vertical vertex. Ordinarily, a cut would be made at this vertex corresponding to cut 241. However, since cut 241 has already been made, no additional cut needs to be made at this point.

10   Next, vertex 211 is a non-horizontal/vertical vertex. Edge 221 is a horizontal edge, but cannot be extended at vertex 211 into polygon 200. Accordingly, a cut 244 which is orthogonal to edge 221 is made at vertex 211 into polygon 200 until cut 241 is encountered.

At this point, segmentation of polygon 200 is completed. The primitive

15   elements which make up polygon 200 include rectangles 251 to 254 and right triangle 255. It is noted that in other embodiments, additional processing may be performed to combine rectangles 253 and 254 into a single rectangle.

Returning to Figure 4, in step 96 the optical system response is obtained for each primitive element, given a single coherent light source point. In

20   the case of a rectangular primitive element, defined with the edges

$$x = x_1 = \text{const}, \ x = x_2 = \text{const}, \ y = y_1 = \text{const}, \ y = y_2 = \text{const},$$
$$\text{where } x_1 < x_2 \text{ and } y_1 < y_2,$$

25   and when the mask is exposed to the monochromatic wave:

$$e^{i(k_x'x + k_y'y)},$$

it can be shown that the complex amplitude of the electric field at the image plane

30   is given by:

$$H^{rect}\left(x,y,k_x,k_y,x_1,x_2,y_1,y_2\right) = e^{i\left(k_x^s x + k_y^s y\right)} \sum_{v=1}^{4} s_v Z_x\left(x - x_v, k_x^s\right) Z_y\left(y - y_v, k_y^s\right) \quad (4)$$

where index v numerates the vertices of the rectangles; and $s_v = 1$ for $x_v = x_2$ and $y_v = y_2$, $s_v = 1$ for $x_v = x_2$ and $y_v = y_1$, and $s_v = -1$ elsewhere. Function $Z_\xi(X.k)$ depends on the type of aperture. For example, if the exit aperture is a

5   square window with dimensions $a \times a$, then:

$$Z_\xi(X,k) = \frac{1}{2k_m}\left[Si\left(\left(k_m + k\right)X\right) + Si\left(\left(k_m - k\right)X\right)\right] - i\left[Cin\left(\left(k_m + k\right)X\right) + Cin\left(\left(k_m - k\right)X\right)\right] \quad (5)$$

where $k_m = \frac{a}{2z}$, z is the distance from exit aperture to image plane, and Si and

Cin are integral *sine* and *cosine* functions, respectively, defined as follows:

10

$$Si(z) = \int_0^z \frac{\sin(t)}{t}dt$$

$$Cin(z) = \int_0^z \frac{1-\cos(t)}{t}dt$$

Let us now consider an object, i.e., an element in the mask pattern, consisting of multiple rectangular primitive elements. The pattern can consists of

15   one or several polygons, with the restriction that it can be represented as a sum of rectangles. The response of the optical system to this pattern can be

represented as a sum of products of the form: $s_v Z_x\left(x - x_v, k_x^s\right) Z_y\left(y - y_v, k_y^s\right)$ taken

over all vertices of the rectangles.

       Generally, many of the vertices of the component rectangles will be

20   common to several different rectangles. Using the previously introduced sign convention, most of the sum terms can be canceled out. For example, if vertices

of four of the rectangles meet at a certain point, the total contribution from that point is equal to zero. Consequently, all the vertices that fall inside the pattern are excluded from the sum, as is each vertex that belong to a single straight edge in the composite mask pattern element. What finally remains in the sum are only those rectangle vertices that are also vertices of the composite element.

Now, a formula for determining the light field at the resist plane due to a composite element consisting of rectangles in the mask plane is:

$$H\left(x,y,k_x^s,k_y^s\right) = e^{i\left(k_x^s x + k_y^s y\right)} \sum_{all-vertices} s_v \, Z_x\left(x - x_v, k_x^s\right) Z_v\left(y - y_v, k_y^s\right) \quad (6)$$

Equation (6) thus illustrates that the manner of decomposing an element into rectangles generally is irrelevant and that the optical system response to a polygon comprised of rectangles can be determined without decomposing the polygon into rectangles. Thus, any polygons which can be decomposed into rectangles can be easily used as primitive elements in the present invention. Similarly, equation (6) can be utilized in a pre-processing routine to reduce the number of rectangular vertices that need to be considered when determining responses to rectangular primitives in step 98.

Referring to Figure 7, The procedure for determining the optical system response to a right triangular primitive element 300 of arbitrary dimensions preferably is as follows:

1. The right triangular primitive element 300 is described by the coordinates of its right angle (x_1, y_1) and the length of its sides, as illustrated in Figure 7. In the present example it will be assumed that right triangular primitive element 300 is an isosceles triangle, although it should be noted that triangular primitives according to the present invention are not limited to isosceles triangles.

2. Triangular primitive element 300 is decomposed into a number of rectangles and smaller triangles, as illustrated in Figure 7. As shown in Figure 7, right triangle 300 is comprised of rectangles, such as rectangles 301 to 304, and smaller triangles. These smaller triangles include positive triangles

whose responses are added to those of the rectangles, such as positive triangles
308 and 309, and negative triangles whose responses are subtracted from those
of the rectangles, such as negative triangles 313 and 314. The dimensions of
these rectangles and smaller triangles is shown in Figure 7, where δ=a/L, a is the
length of a side of the triangle, and L is an integer. The optical system response
is now given as the sum of the responses of the rectangles and smaller triangles,
as follows:

$$H^{triangle}(x,y,k_x^i,k_y^i,x_1,y_1,a) = \sum_{m=0}^{L-1} H^{rect}(x,y,k_x^i,k_y^i,x_1 + 2m\delta,x_1 \cdot 2(m+1)\delta,y_1 \cdot (a-\delta) - 2m\delta,y_1)$$

$$+ \sum_{m=0}^{L-1} H^{rriangle}$$

(7)

3.   The term that corresponds to the rectangles, according to
equation (6) above, can be transformed into the following form:

$$\sum_{m=0}^{L-1} H^{rect} = \frac{e^{i(k_x^i x + k_y^i y)}}{4 k_{mx} k_{my}} \left[Z_y(y_1,k_y^i)[Z_x(x_1,k_x^i) - Z_x(x_1 + 2L\delta,k_x^i)] \right.$$

$$\left. + \sum_{m=0}^{L-1} Z_y(y_1 + (a-\delta) - 2m\delta,k_y^i)[Z_x(x_1 + 2(m+1)\delta,k_x^i) - Z_x(x_1 + 2m\delta,k_x^i)] \right]$$

(8)

4.   It can be shown that the relative contribution of the smaller
triangles to the optical system response to the right triangular primitive element is
less than 10^{-3} of the total response when a right triangle with sides equal to λ (the
wavelength of the incident light) is represented with 16 rectangles.

5.   When higher precision is necessary, for smaller triangles with
dimensions less than λ, the contribution of the smaller triangles can be given as:

$$H_1^{rriangle}(x,y,k_x^i,k_y^i,x_1,y_1,a) = \frac{e^{i(k_x^i x + k_y^i y)}}{4 k_m^2} \{Z(y - y_1,k_y^i)[Z(x - x_1,k_x^i) - Z(x - (x_1 + a),k_x^i)]\}$$

$$+ J_\Delta(x - x_1,y - y_1 - a,k_x^i,k_y^i,a)\}$$

(9)

where

$$JA\left(x,y,k_x^s,k_y^s,a\right) = \int_0^a Z'\left(x_1 - \xi,k_x^s\right)Z'\left(y_1 - \xi,k_y^s\right)d\xi \quad (10)$$

and Z' denotes the first derivative of Z over the first argument.

5   To calculate J_A, the Gauss quadratic formula is used, as follows:

$$JA\left(x,y,k_x^s,k_y^s,a\right) = \frac{a}{2}\sum_{k=1}^{n} A_k^{(n)}F\left(\eta = X_k^{(n)}\right) \quad (11)$$

where

$$F(\eta) = Z'\left(x - \xi(\eta),k_x^s\right)Z'\left(y - \xi(\eta),k_y^s\right), \quad \xi(\eta) = \frac{a}{2}(\eta + 1), \quad x_k^{(n)} \text{ are the zeros}$$

of Legendre polynomials, and $A_k^{(n)}$ are the coefficients of the Gauss quadratic

10   formula.

            While the foregoing technique is utilized to determine optical system
response to triangular primitive elements in the preferred embodiment of the
invention, it should be noted that other techniques also may be used. Moreover,
as noted above, other types of primitive elements also may be used. Also, rather

15   than calculating the response to the primitive elements in step 96, responses may
be pre-stored for standard primitive elements and then simply retrieved from
memory in step 96. Pre-storing responses to standard primitive elements may
increase simulation processing speed, as well as providing the opportunity to use
primitive elements for which closed form response equations can not be derived

20   or for which responses are difficult to calculate on-the-fly.

            Returning to Figure 4, in step 98 the responses from all primitive
elements are combined to obtain an overall mask response function. Preferably,
this step is performed simply by summing the responses for all primitive elements
identified in step 94. In the present embodiment, the overall mask response

25   function is thus given as:

22

$$H(x,y,k_x^s,k_y^s) = \sum_{all-rect} H^{rect}(x,y,k_x^s,k_y^s) + \sum_{all-triang} H^{triangle}(x,y,k_x^s,k_y^s) \quad (12)$$

In step 100, the light intensity at the image plane is determined by combining the responses over all light source points. Preferably, this step is performed by integrating over all points of light source using the following
5 expression:

$$I(x,y) = \int S_B(k_x^s,k_y^s)\left|H(x,y,k_x^s,k_y^s)\right|^2 dk_x^s dk_y^s \quad (13)$$

where $S_B(k_x^s,k_y^s)$ is the Fourier transform of the two-point coherence function.

For example, for a light source with a circular aperture, uniform distribution and coherence parameter σ [3], S_B is known to be:

10
$$S_B = \begin{cases} \dfrac{1}{\pi(k\sigma)^2} & for\left(k_x^s\right)^2 + \left(k_y^s\right)^2 \leq (k\sigma)^2 \\ 0 & elsewhere \end{cases} \quad (14)$$

where $k=2\pi/\lambda$.

In the preferred embodiment of the geometric aerial simulation, transmissive portions of the mask are divided into primitive elements, responses for the primitive elements are determined, and then an overall mask response is
15 determined. In the foregoing embodiment, the responses of all primitive elements to a single point light source are summed and then the responses are evaluated and combined over all light source points. However, it should be understood that this particular order is not strictly necessary. Instead, steps 98 and 100 can be interchanged or can be combined into a single step.
20   By dividing mask transmissive portions into primitive elements, obtaining responses for those primitive elements, and then determining the overall mask response based on the responses from the primitive elements, the present invention often can avoid many of the problems with the prior art techniques. Specifically, the geometric aerial image simulation technique of the
25 present invention generally can avoid the need to rasterize the mask pattern,

23

thereby avoiding rasterization errors. At the same time, the present technique often can be performed relatively quickly. In this regard, as noted above, in many instances the response of a primitive element can be found using only the vertices of the primitive element. In addition, if standard primitive elements are

5   used, the primitive element responses can be pre-stored, thus further reducing the amount of time required to simulate an aerial image.

Finally, by utilizing a geometric aerial image simulation technique according to the present invention, it is often much easier to calculate light intensity only in a small arbitrarily selected portion of the image plane.

10   Conventional techniques, by contrast, often use FFT-based algorithms generally require simulation of the entire image plane. This can be a great advantage of the present technique, because it is frequently only desirable to know light intensity in certain selected portions of the image plane, such as near feature edges.

15

B.   Hybrid Aerial Image Simulation.

An embodiment of a hybrid aerial image simulation technique according to the present invention will now be described with reference to the flow diagram shown in Figure 8. Briefly, according to Figure 8, the mask pattern

20   data are input; the transmissive portions of the mask pattern are divided into primitive elements; a spatial frequency function is obtained for each primitive element; the spatial frequency functions are combined to obtained a transformed mask transmission function; the transformed mask transmission function is sampled based on the desired image plane mesh; and the sampled mask

25   transmission function is then used to simulate the aerial image.

In more detail, in step 392, the mask pattern data are input. Typically, the transmissive portions of the mask pattern are specified in GDS2 format.

In step 394, the transmissive portions of the mask pattern data are

30   divided into primitive elements. Preferably, the primitive elements are rectangles and right triangles. However, as discussed above, other types of primitive

24

elements may instead be used. More preferably, this step is performed in the same manner as step 94 (shown in Figure 4 above).

In step 396, a spatial frequency function is obtained for each of the primitive elements. Preferably, the spatial frequency functions are Fourier

5   transforms of the corresponding primitive elements. However, the spatial frequency functions instead may be obtained using other types of transformations, such as by using a cosine transformation. Also, as noted above, it is preferable that the primitive elements are rectangles and triangles. For an arbitrary rectangle, such as rectangle 430 shown in Figure 9A, it can be shown

10   that the Fourier transform is given as follows:

$$F(\xi, \eta) = \Delta x \frac{Sin\left(\lambda \frac{\Delta x}{2} \xi\right)}{\left(\lambda \frac{\Delta x}{2} \xi\right)} \bullet \Delta y \frac{Sin\left(\lambda \frac{\Delta y}{2} \eta\right)}{\left(\lambda \frac{\Delta y}{2} \eta\right)} \bullet \exp\left\{i\lambda(x_0 \xi + y_0 \eta)\right\} \qquad (15)$$

where (x1,y1) are the coordinates of the lower left corner 431 of rectangle 430, (x2,y2) are the coordinates of the upper right corner 432 of rectangle 430, λ is the wavelength of the incident light, and the transmission function equals 1 within the

15   rectangle and 0 outside the rectangle. Origin 435 can be arbitrarily located; however, it is preferable that origin 435 be fixed relative to the mask for all primitive elements, in order to avoid application of relative phase shifts in step 398. It is noted that, in the present embodiment of the invention, the edges of the rectangular primitive elements will be parallel to the x and y axes. Accordingly,

20   equation (15) above can be used to find the Fourier transform of any rectangular primitive element. If arbitrarily oriented rectangles are intended to be used as primitive elements, a more general formulation of the Fourier transform will have to be used.

For an arbitrary triangle, such as triangle 450 shown in Figure 9B, it

25   can be shown that the Fourier transform is given as follows:

$$F(\xi,\eta) \cdot \frac{1}{\lambda^2 \eta} \left\{ \frac{1}{\xi+k_{01}\eta} \left[e^{i\lambda\left[(\xi-k_{01}\eta)x_1+\eta b_{01}\right]} - e^{i\lambda\left[(\xi+k_{01}\eta)x_0+\eta b_{01}\right]} \right] \right.$$

$$+ \frac{e^{i\lambda\eta b_{12}}}{\xi+k_{12}\eta} \left[e^{i\lambda(\xi+k_{12}\eta)x_2} - e^{i\lambda(\xi+k_{12}\eta)x_1} \right]$$

$$\left. + \frac{e^{i\lambda\eta b_{02}}}{\xi+k_{02}\eta} \left[e^{i\lambda(\xi+k_{02}\eta)x_0} - e^{i\lambda(\xi+k_{02}\eta)x_2} \right] \right\}$$

(16)

where

$$k_{01} = \frac{y_1-y_0}{x_1-x_0}; \quad b_{01} = y_0 - k_{01} \bullet x_0;$$

$$k_{12} = \frac{y_2-y_1}{x_2-x_1}; \quad b_{12} = y_1 - k_{12}x_1;$$

$$k_{02} = \frac{y_2-y_0}{x_2-x_0}; \quad b_{02} = y_2 - k_{02}x_2;$$

5   and where (x1,y1), (x2,y2) and (x3,y3) are the coordinates of the three triangle

vertices 451 to 453, respectively; λ is the wavelength of the incident light; and the

transmission function equals 1 within the triangle and 0 outside the triangle. As

noted above, origin 435 can be placed arbitrarily, but preferably is positioned the

same relative to the mask for all primitive elements.

10   Thus, in the preferred embodiment, the spatial frequency functions

for the primitive elements are calculated analytically on-the-fly. However, it

should be noted that it is also possible to calculate these functions using a

discrete transformation such as the FFT or the Discrete Cosine Transformation

(DCT). This may be desirable, for example, where at least some of the primitive

elements have complicated shapes for which an analytical transformation cannot be easily determined. In this case, it may be possible to use a finer mesh than could be used if, for example, the entire mask pattern had to be transformed using the FFT. Also, if standard primitive elements are used, the spatial

5   frequency transformations generally can be pre-stored.

In step 398, the spatial frequency functions for the primitive elements making up the mask pattern are combined to obtain the transformed mask transmission function. In the preferred embodiment, in which equations (15) and (16) are used to determine the primitive elements' spatial frequency

10   transformations, and assuming that the same origin 435 is used for all primitive elements, this step merely involves adding the spatial frequency functions for the primitive elements. Thus, the transformed mask transmission function is given as follows:

$$F_U\left(\vec{\rho}\right) = \sum_{l=1}^{L} F_{rect_l}\left(\vec{\rho}\right) + \sum_{p=1}^{P} F_{triang_p}\left(\vec{\rho}\right) \quad (17)$$

15   However, if spatial frequency functions are pre-stored, or if different origins are used for different primitive elements, it may be necessary to multiply some or all of the spatial frequency functions for the primitive elements by an appropriate phase shift, in order to reflect their relative positions in the mask, prior to adding them.

20   In step 400, the transformed mask transmission function is sampled. The sampling step size generally can be independent of the mask features and, in particular, independent of the mask feature sizes. Instead, the step size can be chosen based on the desired resolution in the image plane and based on the limitations of the optical system. In this latter regard, the step size generally

25   should be not larger than:

$$\frac{\lambda}{2NA(1+\sigma)} \quad (18)$$

where λ is the wavelength of the incident light, NA is the numerical aperture of the optical system, and σ is the coherence parameter of the light source.

Finally, in step 402 the sampled mask transmission function is used to simulate the aerial image. In the preferred embodiment of the invention, this

5 step is performed by combining the mask transmission function with the optical system coherent transmission function, performing an inverse spatial frequency transformation, and then evaluating over all light source points, such as according to equation (2) above. More preferably, equation (2) is evaluated using a number of processors to separately simulate portions of the aerial image, such as using

10 the following technique.

First, the aerial image plane is divided into a number of non-overlapping rectangles. Then, the aerial image is evaluated in each such rectangle by dividing the mask plane into a number of rectangles, where the area of each rectangle in the mask plane is primarily responsible for the portion of the

15 aerial image in a corresponding rectangle in the aerial image plane. Generally, such rectangles in the mask plane will be larger than their corresponding rectangles in the image plane, and therefore will have to overlap. For example, if light is incident on the mask plane at 90 degrees, the rectangles in the mask plane will be directly above the corresponding rectangles in the aerial image

20 plane, but generally will be larger than the rectangles in the aerial image plane. It is preferable that the rectangles in the mask plane have dimensions of approximately twice the dimensions of the rectangles in the image plane. Generally, accurate results can be obtained by using rectangles in the mask plane having dimensions of at least 2λ/(NA) with corresponding rectangles in the

25 aerial image plane being the center rectangles of those in the mask plane and having dimensions of λ/(NA), where λ is the wavelength of the incident light and NA is the numerical aperture.

While the above describes a representative embodiment of hybrid simulation according to the present invention, numerous variations are possible.

30 For example, sampling step 400 could be performed prior to combining step 398. Also, other simulation formulas may be used in step 402.

28

Hybrid aerial image simulation according to the present invention can be used in mask design, such as in step 44 (shown in Figure 2). After aerial image simulation, it may be desirable to alter the mask pattern by adding or replacing correction elements, such as serifs. See, for example, step 50 shown in

5   Figure 2 above. In the event of such mask alteration, the new transformed mask transmission function can be easily calculated using the present hybrid technique. Specifically, the new transformed mask transmission function is the previous mask transmission function plus the sum of the spatial frequency transformations of the new correction elements minus the sum of the spatial frequency

10   transformations of the replaced correction elements. Mathematically, this is given as follows:

$$Fu_{new}(\vec{\rho}) = Fu_{prev}(\vec{\rho}) + \sum_{j=1}^{J} F_{corr_{new}} - \sum_{k=1}^{K} F_{corr_{rpl}} \quad (19)$$

It is noted that the spatial frequency functions of the correction elements can be determined in the same manner as described above for the primitive elements.

15   Thus, the hybrid aerial image simulation according to the present invention generally can avoid many of the problems associated with conventional techniques. First, rasterization errors which are present in many conventional techniques can be largely eliminated. Second, a relatively coarse FFT mesh often can be utilized, increasing computation speed while still maintaining good

20   accuracy. Third, the present technique generally permits relatively easy calculation of the effects of adding or replacing correction elements on the resulting aerial image. Fourth, because simulation accuracy generally is unrelated to mask feature size in the present technique, it is usually possible to calculate the effects of small correction elements, i.e., having dimensions much

25   smaller than the resolution of the optical system.

C.   Aerial Image Simulation System Environment.

Generally, the methods described herein, or portions thereof, will be practiced with a general purpose computer, either with a single processor or

multiple processors. For example, a mask pattern can be input and the foregoing steps for simulating an aerial image can then be performed by a computer.

Fig. 10 is an illustration of a general purpose computer system, representing one of many suitable computer platforms for implementing the
5 inventive methods described above. Fig. 10 shows a general purpose computer system 550 in accordance with the present invention includes a central processing unit (CPU) 552, read only memory (ROM) 554, random access memory (RAM) 556, expansion RAM 558, input/output (I/O) circuitry 560, display assembly 562, input device 564, and expansion bus 566. Computer system 550
10 may also optionally include a mass storage unit 568 such as a disk drive unit or nonvolatile memory such as flash memory and a real-time clock 570.

CPU 552 is coupled to ROM 554 by a data bus 572, control bus 574, and address bus 576. ROM 554 contains the basic operating system for the computer system 550. CPU 552 is also connected to RAM 556 by busses 572,
15 574, and 576. Expansion RAM 558 is optionally coupled to RAM 556 for use by CPU 552. CPU 552 is also coupled to the I/O circuitry 560 by data bus 572, control bus 574, and address bus 576 to permit data transfers with peripheral devices.

I/O circuitry 560 typically includes a number of latches, registers and
20 direct memory access (DMA) controllers. The purpose of I/O circuitry 560 is to provide an interface between CPU 552 and such peripheral devices as display assembly 562, input device 564, and mass storage 568.

Display assembly 562 of computer system 550 is an output device coupled to I/O circuitry 560 by a data bus 578. Display assembly 562 receives
25 data from I/O circuitry 560 via bus 578 and displays that data on a suitable screen.

The screen for display assembly 562 can be a device that uses a cathode-ray tube (CRT), liquid crystal display (LCD), or the like, of the types commercially available from a variety of manufacturers. Input device 564 can be
30 a keyboard, a mouse, a stylus working in cooperation with a position-sensing

display, or the like. The aforementioned input devices are available from a variety

of vendors and are well known in the art.

Some type of mass storage 568 is generally considered desirable.

However, mass storage 568 can be eliminated by providing a sufficient mount of

5   RAM 556 and expansion RAM 558 to store user application programs and data.

In that case, RAMs 556 and 558 can optionally be provided with a backup battery

to prevent the loss of data even when computer system 550 is turned off.

However, it is generally desirable to have some type of long term mass storage

568 such as a commercially available hard disk drive, nonvolatile memory such

10   as flash memory, battery backed RAM, PC-data cards, or the like.

A removable storage read/write device 569 may be coupled to I/O

circuitry 560 to read from and to write to a removable storage media 571.

Removable storage media 571 may represent, for example, a magnetic disk, a

magnetic tape, an opto-magnetic disk, an optical disk, or the like. Instructions for

15   implementing the inventive method may be provided, in one embodiment, to a

network via such a removable storage media.

In operation, information is inputted into the computer system 550

by typing on a keyboard, manipulating a mouse or trackball, or "writing" on a

tablet or on position-sensing screen of display assembly 562. CPU 552 then

20   processes the data under control of an operating system and an application

program stored in ROM 554 and/or RAM 556. CPU 552 then typically produces

data which is outputted to the display assembly 562 to produce appropriate

images on its screen.

Expansion bus 566 is coupled to data bus 572, control bus 574, and

25   address bus 576. Expansion bus 566 provides extra ports to couple devices

such as network interface circuits, modems, display switches, microphones,

speakers, etc. to CPU 552. Network communication is accomplished through the

network interface circuit and an appropriate network.

Suitable computers for use in implementing the present invention

30   may be obtained from various vendors. Various computers, however, may be

used depending upon the size and complexity of the tasks. Suitable computers

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include mainframe computers, multiprocessor computers, workstations, or personal computers. In addition, although a general purpose computer system has been described above, a special-purpose computer may also (or instead) be used to implement the methods of the present invention.

5   It should be understood that the present invention also relates to machine readable media on which are stored program instructions for performing methods of this invention. Such media includes, by way of example, magnetic disks, magnetic tape, optically readable media such as CD ROMs, semiconductor memory such as PCMCIA cards, etc. In each case, the medium may take the form of a portable item such as a small disk, diskette, cassette, etc., or it may take the form of a relatively larger or immobile item such as a hard disk drive or RAM provided in a computer.

D.   Conclusion.

15   Although the present invention has been described in detail with regard to the exemplary embodiments and drawings thereof, it should be apparent to those skilled in the art that various adaptations and modifications of the present invention may be accomplished without departing from the spirit and the scope of the invention. Accordingly, the invention is not limited to the precise embodiments shown in the drawings and described in detail above. Therefore, it is intended that all such variations not departing from the spirit of the invention be considered as within the scope thereof as limited solely by the claims appended hereto.

In the following claims, those elements which do not include the words "means for" are intended not to be interpreted under 35 U.S.C. § 112 ¶ 6.

CLAIMS

What is claimed is:

1.   A method for simulating an aerial image produced by a mask having transmissive portions, said method comprising:

(a)   dividing the transmissive portions of the mask into primitive

5   elements;

(b)   obtaining a spatial frequency function corresponding to each of the primitive elements;

(c)   combining the spatial frequency functions corresponding to the primitive elements to obtain a transformed mask transmission function; and

10   (d)   utilizing the transformed mask transmission function to generate a simulation of the aerial image.

2.   A method according to Claim 1, wherein at least two of the primitive elements have different shapes.

3.   A method according to Claim 1, wherein the primitive elements include at least one rectangle and at least one triangle.

4.   A method according to Claim 1, wherein the spatial frequency function corresponding to said each of the primitive elements obtained in step (b) is determined analytically.

5.   A method according to Claim 1, wherein the aerial image is simulated by combining the transformed mask transmission function with an optical system coherent transmission function and performing an inverse spatial frequency transformation.

6.   A method according to Claim 1, further comprising a step of combining aerial images for all light source points.

7.   A method according to Claim 1, further comprising:

(e)   modifying the mask based on the simulated aerial image by adding correction elements to the mask; and

(f)   determining a new transformed mask transmission function by

5   combining spatial frequency functions corresponding to the added correction elements with the transformed mask transmission function obtained in step (c).

8.   A method according to Claim 1, wherein the spatial frequency functions corresponding to the primitive elements are obtained by using a Fourier transform.

9.   A method according to Claim 1, wherein the primitive elements consist only of triangles and rectangles.

10.   A method according to Claim 1, wherein the transformed mask transmission function is sampled using a step which is independent of mask features.
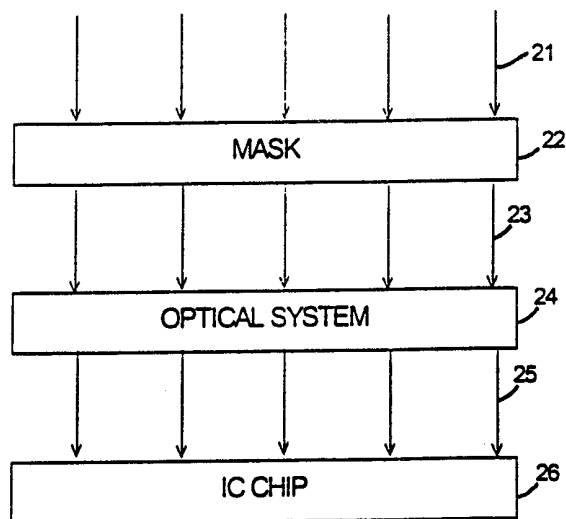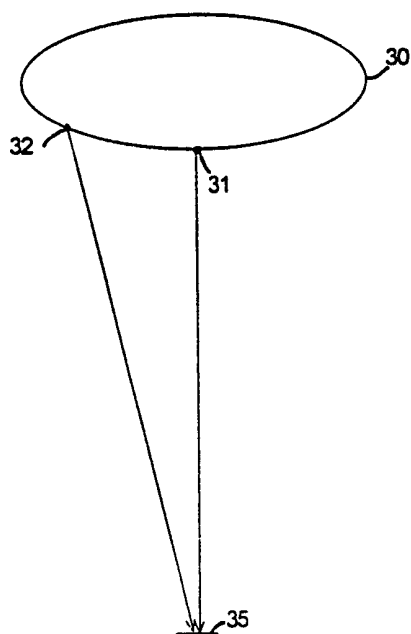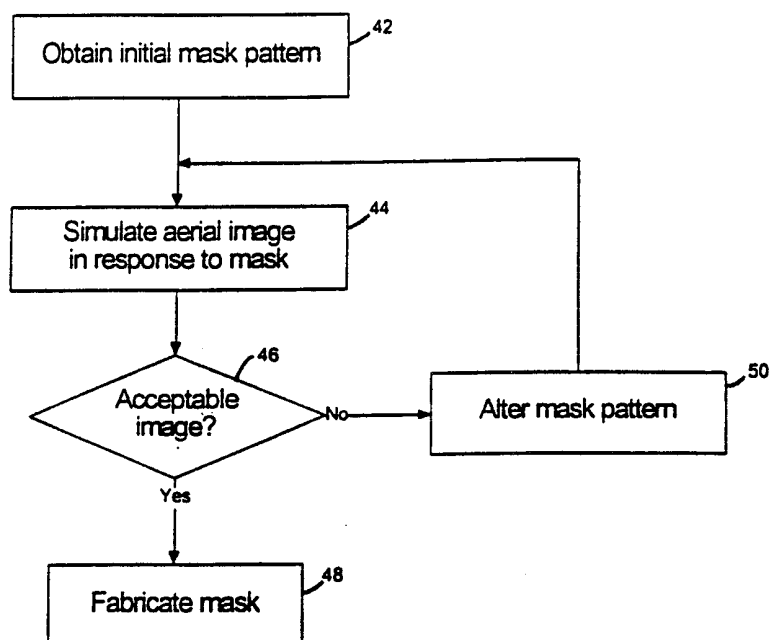
11.   A method for simulating an aerial image produced by a mask having transmissive portions, said method comprising:

(a)   dividing the transmissive portions of the mask into primitive elements;

5   (b)   obtaining a spatial frequency function corresponding to each of the primitive elements;

(c)   combining the spatial frequency functions corresponding to the primitive elements to obtain a transformed mask transmission function; and

(d)   simulating the aerial image by combining the transformed mask

10   transmission function with an optical system coherent transmission function and performing an inverse spatial frequency transformation,

wherein at least two of the primitive elements have different shapes.

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12.   A method according to Claim 11, wherein the spatial frequency function corresponding to said each of the primitive elements obtained in step (b) is determined analytically.

13.   A method according to Claim 11, further comprising a step of combining aerial images for all light source points.

14.   A method according to Claim 11, further comprising:

(e)   modifying the mask based on the simulated aerial image by adding correction elements to the mask; and

(f)   determining a new transformed mask transmission function by combining spatial frequency functions corresponding to the added correction elements with the transformed mask transmission function obtained in step (c).

15.   A method according to Claim 11, wherein the spatial frequency functions corresponding to the primitive elements are obtained by using a Fourier transform.

16.   A method according to Claim 11, wherein the primitive elements consist only of triangles and rectangles.

17.   A method according to Claim 11, wherein the transformed mask transmission function is sampled using a step which is independent of mask features.

MASK

OPTICAL SYSTEM

IC CHIP

FIG. 1A

FIG. 1B

```
                    ┌──────────────────────────┐ 42
                    │ Obtain initial mask pattern│
                    └──────────────────────────┘
                                 │
                                 ▼
                    ┌──────────────────────────┐ 44
                    │   Simulate aerial image   │
                    │    in response to mask    │
                    └──────────────────────────┘
                                 │
                                 ▼
                            46
                          ◇─────────◇
                         /  Acceptable \      No      ┌──────────────────────┐ 50
                        <    image?      >─────────▶  │   Alter mask pattern  │
                         \             /              └──────────────────────┘
                          ◇─────────◇
                               │
                              Yes
                               │
                               ▼
                    ┌──────────────────────────┐ 48
                    │      Fabricate mask        │
                    └──────────────────────────┘
```

FIG. 2

FIG. 3A

FIG. 3B

Input mask data — 92

↓

Divide transmissive portions
into primitive elements — 94

↓

Obtain optical system response
for each primitive element,
assuming a single coherent light source point — 96

↓

Combine responses over all primitive elements
to obtain mask response — 98

↓

Find the light intensity at the image plane
by combining responses over all light source
points — 100

FIG. 4

```
                    ┌──────────────────┐ ⌐122
                    │ Select first vertex │
                    └──────────────────┘
                              │
          ┌───────────────────┤
          │                   ▼
          │              ◇⌐124
          │            ╱        ╲
          │          ╱  Inner angle, ╲      ⌐126
          │         ◇ horizontal/vertical ◇──Yes──▶┌──────────────┐
          │          ╲   vertex?    ╱             │ Continue edge │──┐
          │            ╲          ╱               └──────────────┘  │
          │                 │                                        │
          │                 No                                       │
          │                 ▼                                        │
          │              ◇⌐128                                       │
          │            ╱        ╲            ⌐130                     │
          │          ╱ Non-horizontal/ ╲    ┌──────────────┐         │
          │         ◇  vertical vertex? ◇──Yes──▶│Form horizontal│    │
          │          ╲             ╱    │ or vertical cut │         │
          │            ╲         ╱      └──────────────┘         │
          │                 │              │                       │
          │                 No             │                       │
   ┌───────────┐ ⌐134       ◀──────────────┘◀──────────────────────┘
   │ Select next│           │
   │   vertex   │◀──No── ◇⌐132
   └───────────┘        ╱        ╲
                       ◇ Last vertex? ◇
                        ╲          ╱
                             │
                            Yes
                             ▼
                      ( Next polygon )
```

FIG. 5

FIG. 6A

FIG. 6B

FIG. 7

Input mask data 392

Divide transmissive portions into primitive elements 394

Obtain spatial frequency function for each primitive element 396

Combine spatial frequency functions for primitive elements to obtain transformed mask transmission function 398

Sample transformed mask transmission function 400

Use sampled mask transmission function to simulate aerial image 402

FIG. 8

FIG. 9A

FIG. 9B

FIG. 10

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G03F 9/00; G06F 3/00, 9/455

US CL :430/5; 395/500.22

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 430/5, 22; 395/500.22

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,801,954 A [LE et al] 01 September 1998, col. 5, line 20 to col. 6, line 52.	1-17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 APRIL 2000	0 5 MAY 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	STEPHEN ROSASCO
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0651

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