

[54] **INTENSITY SPATIAL FILTER HAVING
NON-UNIFORMLY SPACED FILTER
ELEMENTS**

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[51] Int. Cl. **G01n 21/32, G02b 27/38**

[58] Field of Search **350/162 SF, 3.5; 356/71, 168, 200, 237, 239; 250/219 CR, 219 DF**

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Primary Examiner—David Schonberg

Assistant Examiner—Ronald J. Stern

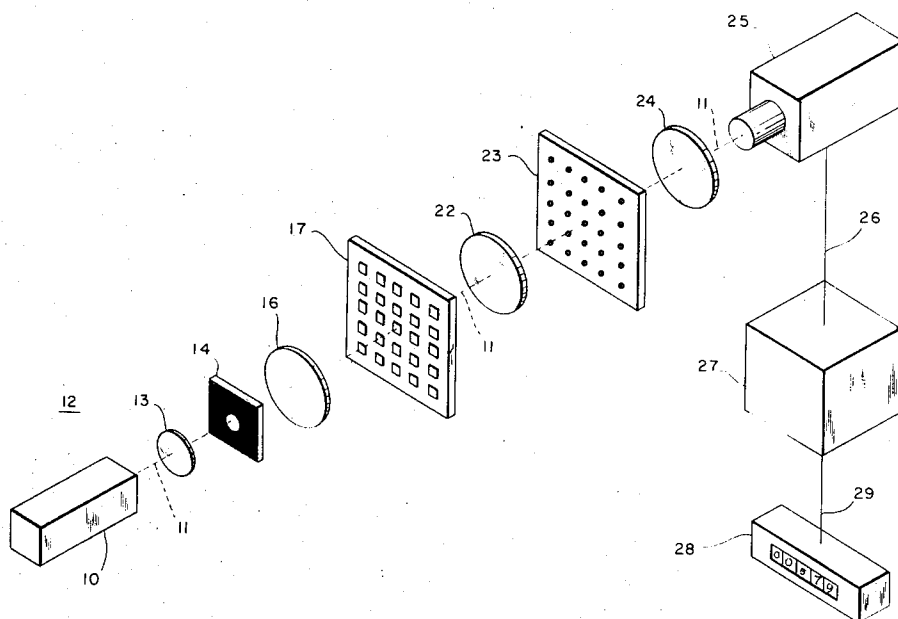
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[57]

ABSTRACT

A spatial filtering system for inspecting integrated circuit photomasks, and the like. The system employs a spatial filter comprising a matrix-like array of opaque regions on a transparent field. Unlike prior art systems where the region-to-region spacing of the filter is uniform, in the instant invention the region-to-region spacing steadily increases from the centermost element outward according to a precise mathematical formula.

4 Claims, 8 Drawing Figures



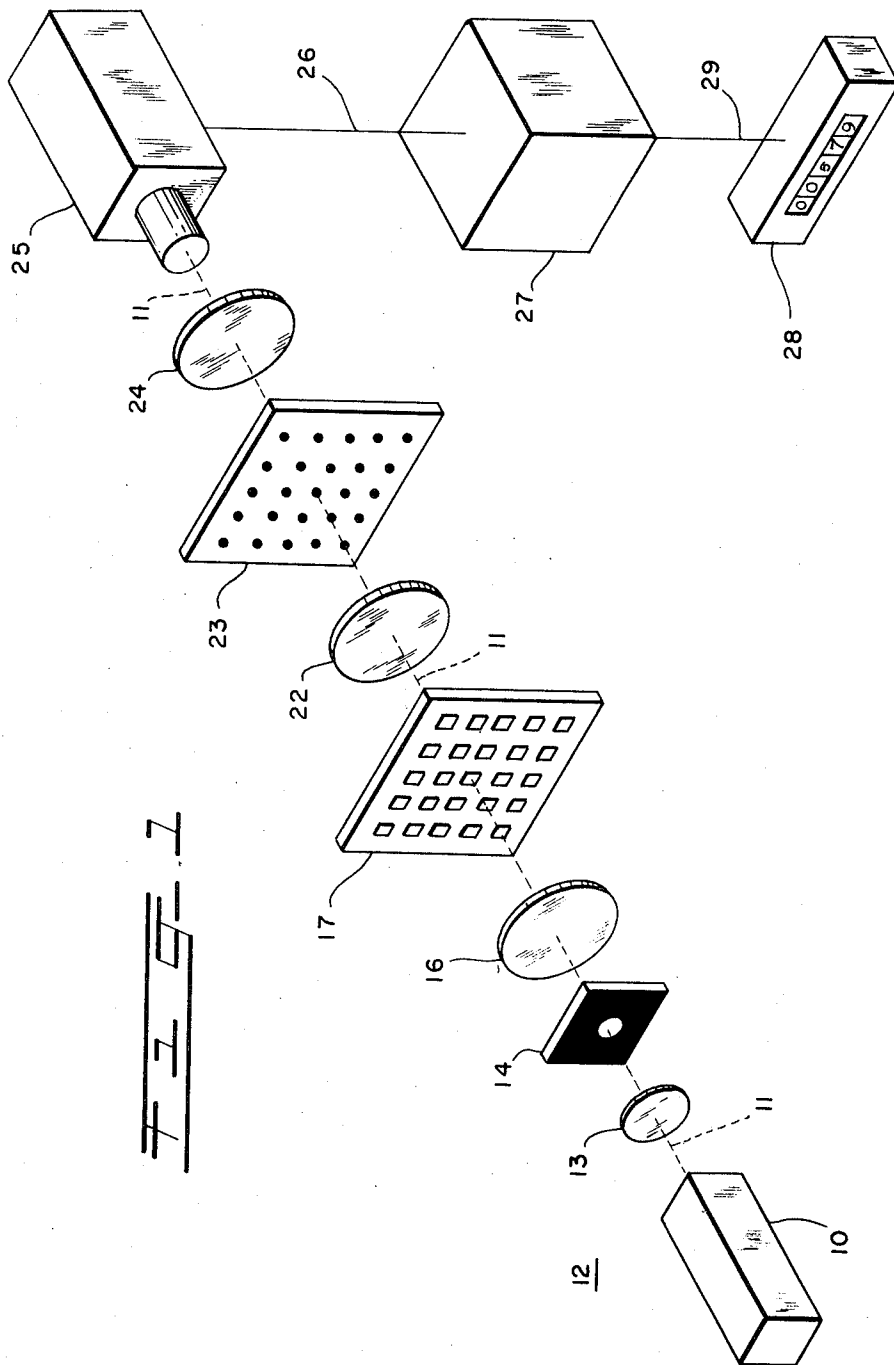


Fig. 1

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SHEET 2 OF 3

FIG. 2

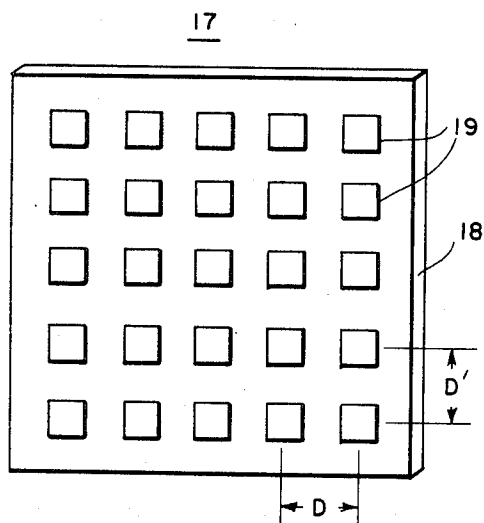


FIG. 3

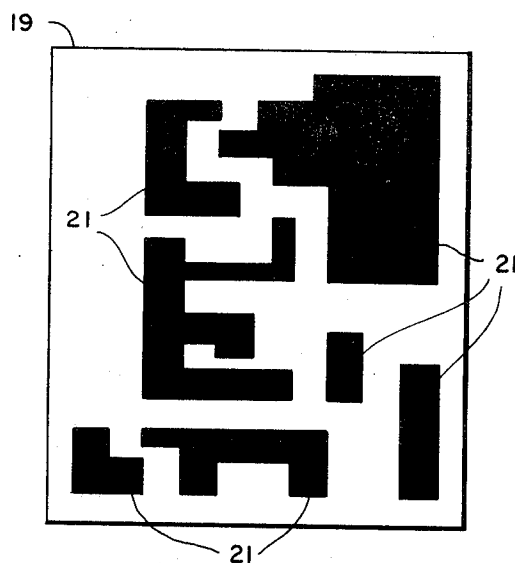


FIG. 4

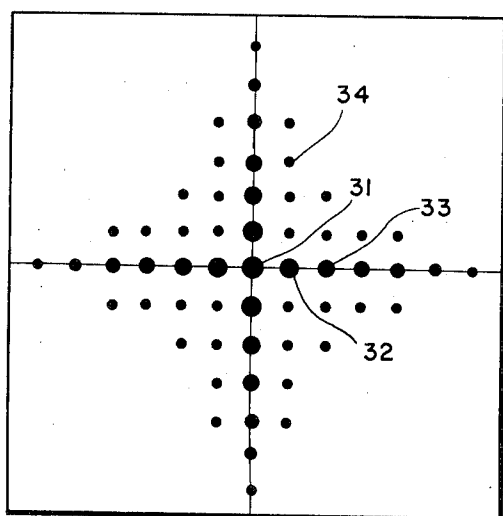
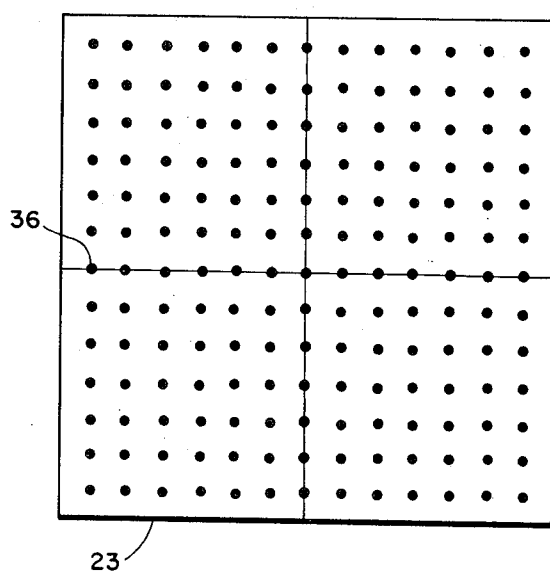
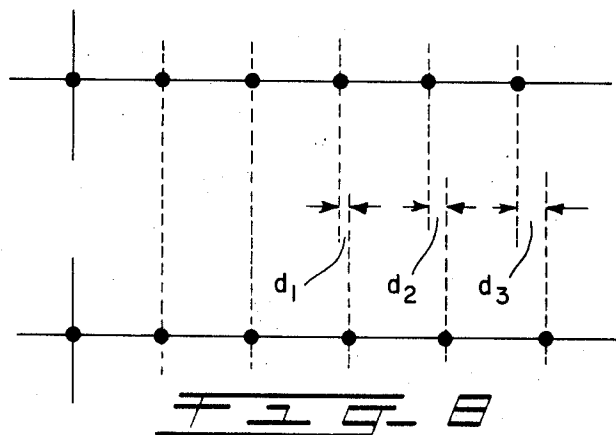
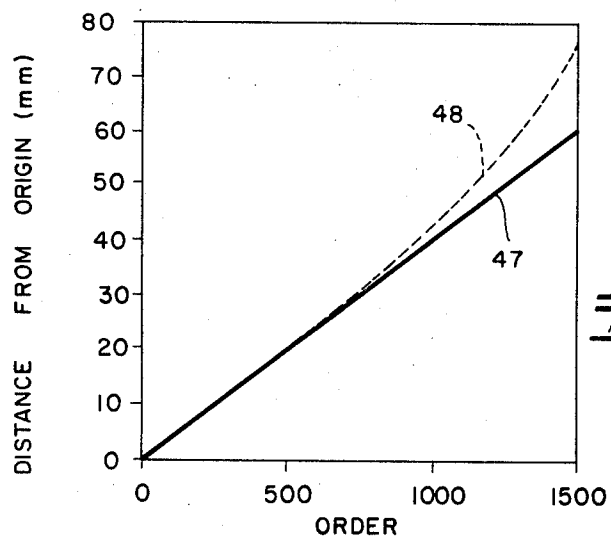
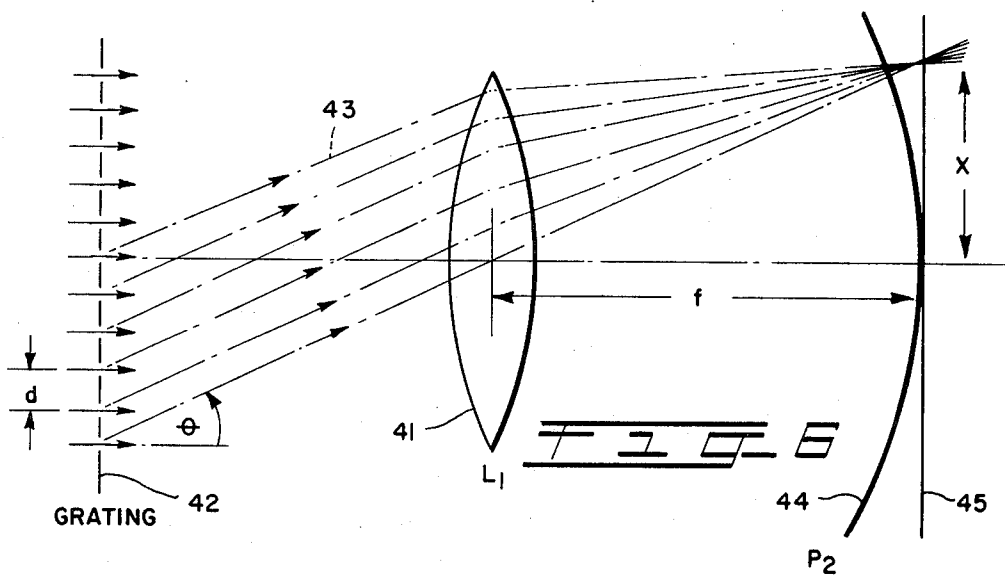


FIG. 5





INTENSITY SPATIAL FILTER HAVING NON-UNIFORMLY SPACED FILTER ELEMENTS

BACKGROUND OF THE INVENTION

1. Field of the Invention

Broadly speaking, this invention relates to spatial filtering. More particularly, in a preferred embodiment, this invention relates to an improved spatial filtering system which inhibits transmission of substantially all periodic information in the filtered image, thereby significantly improving the signal-to-noise ratio of the system.

2. Discussion of the Prior Art

As is well known, in the manufacture of integrated circuits, and the like, wafers of silicon, or other semiconductor material, are coated with a layer of photoresist and, then, exposed to light through a special photographic plate, known in the industry as a photomask. The exposed photoresist is then developed, in the conventional manner, and unexposed areas of the photoresist are removed, thereby, exposing underlying portions of the silicon wafer. These exposed portions are then subjected to processing steps, such as diffusion, etching, and the like.

A typical IC photomask may comprise a matrix-like array of thousands of nominally identical photomask features, each in itself a complex pattern of lines and other geometric shapes. Such photomasks have heretofore been made by successive photographic reductions from a large, hand-made master pattern, in a step-and-repeat camera, or more recently, by direct exposure of a photographic plate or chromium coated plate in a computer-controlled electron beam machine. More recently still, a primary pattern generator (PPG), a computer-controlled, electro-mechanical, laser deflection system, has been successfully employed to manufacture IC photomasks [See *Bell System Technical Journal*, (Nov. 1970), Vol. 49, No. 9, pages 2031-2076].

However, regardless of the manufacturing process employed, IC photomasks are expensive and time consuming to make. Accordingly, every effort is made to prolong their useful life. Because of the extremely high resolution required with modern IC devices, exposure of photoresist-covered silicon wafers can only be satisfactorily accomplished by a contact-printing process, in which the emulsion side of the photomask is placed in direct physical contact with the wafer. This frequently results in damage to the mask during exposure. Furthermore, pinhole defects may occur during manufacture of the photomask itself, and dust or dirt may settle on the mask during use.

These defects are, of course, very serious, for any wafer exposed to light through a damaged or dirty photomask may yield dozens of defective, or wholly inoperative, IC devices. This situation is further aggravated by the fact that the same photomask is used over and over again. Thus, a given defect on a mask might be responsible for thousands of defective IC devices, a most undesirable situation.

As previously discussed, IC photomasks are too expensive to be discarded after they have been used only a few times. Accordingly, it becomes necessary to carefully inspect each mask after manufacture and also, somewhat less critically, during actual production. Heretofore, these inspections were done manually by a skilled human operator, with the aid of a microscope. However, because of the complex nature of the geo-

metric pattern in each photomask feature, as well as the fact that each mask contains many thousands of identical features, human error and fatigue have been found to result in the failure to detect significant numbers of defects.

To overcome this problem, a spatial filtering technique was developed to inspect the photomasks. This technique forms the subject matter of copending U. S. Pat. application, Ser. No. 858,002, filed Sept. 15, 1969, (Watkins Case 1), which application is assigned to the assignee of the instant invention.

As disclosed in said copending application, the photomask to be inspected is illuminated by spatially coherent radiation from a laser and positioned proximate the front-focal plane of a convex lens. In accordance with well-known optical principles, an image will be formed at the rear-focal plane of the lens which corresponds to a Fourier transform of the photomask. That is to say, the image is a composite diffraction pattern whose spatial distribution is the optical product of two components: (1) the interference function of the photomask, comprising a distribution of bright dots of light whose spacing is inversely proportional to the spacing between adjacent features in the mask; and (2) the diffraction pattern of a single feature. Now, as disclosed in said copending application, if a spatial filter comprising an array of opaque regions on a transparent field, is positioned proximate the back-focal plane of the lens, and if the spacing between the opaque regions corresponds exactly to the spacing between the dots of light in the diffraction pattern, substantially all of the light energy from the laser will be blocked.

However, if the mask is defective in some way, for example, if the mask is scratched, etc., the Fourier transform of the defect will not spatially correspond to the pattern of opaque regions on the filter, and accordingly, some light will succeed in passing through the filter, thereby enabling the scratch or other defect to be easily detected.

The above-described spatial filtering technique has been highly successful in practice. However, certain problems were encountered when an attempt was made to automate the inspection process. For example, in order to eliminate the human factor, a television camera, coupled to a counting device, was positioned to view the filtered image of the mask. As the camera scanned over the image, the counting device recorded the number of defects detected, and, if the value so found exceeded some predetermined value, the mask was discarded, or set aside for possible repair.

The system disclosed in copending application, Ser. No. 858,002, (Watkins Case 1) assumed, for the sake of simplicity, that the interference function produced by a lens comprises equally spaced dots. In practice, this is not exactly so, and the lens generates an interference function in which the dots become progressively further apart by very small increments. Furthermore, the lens may suffer from one or more optical aberrations, such as coma, astigmatism, field curvature, and distortion. The net effect is that, as the light energy impinges on those parts of the filter which lie further and further away from the center of the filter, the opaque regions thereon no longer fully block the light which is coming from the photomask, even in the total absence of defects on the mask. This is so for two reasons: first, the outermost regions are improperly positioned to fully intercept the light from the photomask, even if it

were properly focused on the regions. Secondly, because the opaque regions are physically located on a planar surface, the outermost opaque regions lie increasingly a small distance apart from the true focus of the lens, and hence, in effect, become progressively too small to fully block the light from the photomask. The outermost regions, of course, are intended to intercept the higher spatial frequencies from the photomask and, in practice, the only features on the mask possessing such higher spatial frequencies are the edges of the photomask features.

In prior art systems, where the filtered image was inspected by a human operator, this failure to fully suppress periodic, high frequency, edge information did not prove to be a significant problem. In fact, it was somewhat of an advantage, because the outline of the individual photomask features could be seen very faintly in the background of the image, as viewed by the operator. Thus, the approximate location of the non-periodic defects which were successfully isolated by the system could be rapidly ascertained. However, in an automated process, this no longer holds true, because a television camera does not have a human operator's ability to reason and is unable to discriminate between a true defect and the high frequency edge information of the photomask features. Thus, in the automated process, the edge information was erroneously counted as a defect, which it is not. An additional problem with the prior art approach is that, because of the presence of high frequency edge information, only a few of the thousands of features on a mask can be inspected at the same time. Now, if an attempt is made to increase the field of view, that is to say, if instead of inspecting only twenty or so of the thousands of features on a given mask, it is desired to simultaneously examine several hundred features, the spatial filter must, accordingly, be made with considerably more accuracy.

SUMMARY OF THE INVENTION

As a solution to these and other problems, it is one object of this invention to provide a method of spatially filtering an image which suppresses substantially all periodic information in the image, thereby significantly enhancing the signal-to-noise ratio of the image.

It is a further object of this invention to provide a novel construction for a spatial filter to practice the above method.

Accordingly, one embodiment of the invention comprises a method of isolating non-periodic errors in a two-dimensional pattern containing a regular array of nominally identical features, mutually spaced apart, along at least one axis, by a predetermined distance. The method comprises the steps of first directing a spatially coherent beam of light at the pattern to diffract the light; and then focusing the diffracted light on a filter containing a plurality of discrete opaque regions on a transparent field, the spacing between adjacent regions, along at least one axis of the filter, increasing from region-to-region, from the centermost region outwardly to the edges of the filter, to spatially modulate the light. Next, the spatially modulated light is reimaged to form an image exhibiting the non-periodic errors in the pattern, the filter blocking essentially all periodic information in the image, including the higher spatial frequency components.

For practicing the above method, another embodiment of the invention comprises a spatial filter includ-

ing a matrix-like array of opaque elements on a transparent field, the spacing between adjacent elements of the filter, along at least one axis of the array, increasing from element-to-element from the centermost element outwards to the edges of the array. Thus, when the filter is positioned to intercept the Fourier transform of the image of a workpiece, for example, a workpiece comprising a matrix-like array of nominally identical features, the opaque elements act to inhibit further transmission of substantially all periodic information in the Fourier transform.

In yet another embodiment of the invention, the distance X of any given element along said at least one axis, measured from the centermost element on the filter, is given by the formula:

$$X = f \tan [\sin^{-1} (n\lambda/d)]$$

where,

f = the focal length of the Fourier transform lens;
 λ = the wavelength of the light forming said image;
 n = the order of the spatial harmonic;
 d = the step-and-repeat of the workpiece.

The invention, and its mode of operation will be more fully understood from the following detailed description, and the following drawing, in which:

DESCRIPTION OF THE DRAWING

FIG. 1 is a partially schematic, isometric view of a first embodiment of the invention;

FIG. 2 illustrates a typical workpiece of the type which may be inspected by the instant invention;

FIG. 3 shows an enlarged view of a portion of the workpiece shown in FIG. 2;

FIG. 4 depicts the format of the diffraction pattern produced when the workpiece of FIG. 2 is inspected by the apparatus of FIG. 1;

FIG. 5 depicts an illustrative prior art spatial filter;

FIG. 6 is a diagram illustrating the theory underlying the instant invention;

FIG. 7 is a graph showing the spacing of filtering elements on the filter of FIG. 5, as a function of the spatial harmonic; and

FIG. 8 depicts the relative orientation of the filtering elements of a prior art filter and the filter according to this invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 depicts an illustrative embodiment of the invention. As shown, the apparatus comprises a laser 10 which, when connected to a suitable source of energy (not shown), emits a beam of spatially coherent, radiant energy along a longitudinal axis 11. The light from laser 10 is directed through a beam expander 12, comprising a first lens 13 and pinhole 14. The expanded beam is then passed through a collimating lens 16 and finally falls upon the IC photomask 17 to be inspected.

FIGS. 2 and 3 illustrate photomask 17 in greater detail. As shown, the photomask comprises a glass photographic plate 18 having recorded thereon a matrix-like array of nominally identical features 19. As shown in FIG. 3, each feature comprises a complex pattern of opaque areas 21 on a transparent field, the pattern in each feature defining the areas of the photoresist-covered semiconductor wafer which are to be protected from exposure to the light. It will be noted that all of the edges of the areas 21 in feature 19 are parallel to either the horizontal or to the vertical axes of the

mask. By analogy to the orientation of the blocks in a typical city, such a configuration is frequently referred to as "Manhattan" geometry, although, of course, the invention is not limited to inspecting workpieces having such "Manhattan" geometry, and can inspect with equal success other workpiece configurations. It will also be noted that, in FIG. 2, a uniform spacing D is assumed to exist between the center lines of each feature on the mask. It is further assumed that this spacing is the same in both the horizontal and vertical directions (i.e., $D = D'$). Occasionally, a photomask is produced in which the feature-to-feature spacing differs in the horizontal and vertical directions. However, this is easily compensated for in the design of the spatial filter, and the underlying theory of the instant invention applies to both arrangements.

In the drawing, mask 17 is depicted as having a 5×5 matrix of features thereon. One skilled in the art will appreciate that this is merely for convenience in illustrating the invention and that an actual photomask may have as many as 40,000 features thereon arranged in a 200×200 matrix.

Returning now to FIG. 1, photomask 17 is positioned at the front-focal plane of a second lens 22 which, as previously discussed, will form a Fourier transform of the photomask at the back-focal plane thereof. In accordance with the teachings of copending application, Ser. No. 858,002, (Watkins Case 1), spatial filter 23 is positioned at the back-focal plane to intercept all periodic information from photomask 17 and to permit all non-periodic information, such as defects in the photomask, to pass through the filter. The non-periodic information which does succeed in passing through filter 23 is imaged by a third lens 24 for viewing by a television camera 25. As will be explained below, camera 25 is connected by a lead 26 to a control circuit 27, which includes conventional power supplies, amplifiers, deflection apparatus, etc. A digital-readout device 28 is connected to control circuit 27 by a lead 29 to record the number of defects in photomask 17 which succeed in passing through spatial filter 23 and are detected by camera 25.

FIG. 4 illustrates the pattern which would be seen if a screen were to be positioned at the back-focal plane of lens 22, rather than spatial filter 23. For convenience in drawing, this pattern is shown as a series of black dots on a white field. It will be appreciated that, in actual practice, each of the black dots in FIG. 4 represents a spot of bright light. As seen, the pattern approximates a cross with the spacing between adjacent light dots, in the horizontal direction, being inversely proportional to the feature-to-feature spacing in the horizontal direction in mask 17. Similarly, the spacing between adjacent dots, in the vertical direction, is inversely proportional to the feature-to-feature spacing in photomask 17 in the vertical direction. If, as discussed, the feature-to-feature spacing on the mask is uniform, and equal, in both directions, then the dot-to-dot spacing in the diffraction pattern will also be uniform, and equal, in both directions. The large central dot 31 corresponds to the d.c. term of the Fourier transform and, moving to the right, in the horizontal direction, dot 32 corresponds to the first "harmonic," or fundamental spatial frequency, (i.e., the step-and-repeat pattern of the mask), dot 33 the second harmonic, and so on.

FIG. 5 depicts a spatial filter of the type disclosed in the above-referenced copending application, Ser. No. 858,002, (Watkins Case 1). This filter comprises an array of opaque regions on a transparent field. This type of filter can be manufactured by the use of any of several known techniques, in essentially the same manner that the photomask itself may be manufactured. Considerable success has been obtained by the use of the above-referenced primary pattern generator, and a step-and-repeat camera. If, as is usually the case, the feature-to-feature spacing on the mask is uniform, and equal, along both the horizontal and vertical axes, then the array of opaque regions in the spatial filter will also be uniform, and equal, along both axes, and will coincide with the location of light spots 31 through 34, etc., in FIG. 4.

While the intensity and size of the light dots in the actual diffraction pattern of FIG. 4 may vary, the opaque regions in FIG. 5 are typically all uniform in size and density. Of course, the regions must be large enough to block the largest of the light dots shown in FIG. 4.

As previously discussed, the system described in copending application, Ser. No. 858,002, (Watkins Case 1), assumed that the lens was perfect and produced equally spaced dots, and this assumption was reasonable for the inspection scheme contemplated by that invention. However, for more critical applications, this assumption is not valid, and the deviations must be taken into account. In FIG. 6 a lens 41 is shown positioned so that a diffraction grating 42 is at its front-focal plane. The diffraction grating has elements spaced apart by a uniform distance d . Typical light rays 43 are shown coming from the diffraction grating at an angle θ to the horizontal axis, as shown, and are imaged by lens 41 onto the back-focal plane of lens 41.

From basic diffraction theory, it is known that when a plane, collimated beam of light is incident upon an intensity grating, the resulting pattern behind the grating is the superimposition of many plane waves, each propagating in a different direction. The angle θ at which these beams emanate from the grating is a function of the harmonic, n , which they represent, that is:

$$\sin \theta = n \lambda / d \quad (1)$$

where,

λ = the wavelength of light;

n = the order of the harmonic;

d = the step-and-repeat of the array; and

f = the focal length of the Fourier transform lens.

Each of these waves is then focused to a spot in the back-focal plane by the Fourier transforming lens 41. The hemispherical surface 44 has been included to aid in computing the location of these images in the plane 45. The location of the light spots on the plane 45 can then be computed from simple geometry:

$$X = f \tan \theta = f \tan [\sin^{-1} (n \lambda / d)] \quad (2)$$

Since for small angles, i.e., low spatial frequencies, $\sin \theta \cong \tan \theta \cong \theta$, the above equation reduces to the form which was assumed in the above-referenced copending application, (Watkins Case 1), namely,

$$X = n \lambda f/d$$

(3)

FIG. 7 is a graph showing the distance from the origin (center) of the opaque filter regions, as a function of the order of the spatial frequency, for the linear equation assumed in the copending application, and for the actual equation given in Equation 2 above. It will be observed that for the first few orders, the deviation between the linear graph and the actual, approximately tangential, graph is very small, but towards the higher orders, this discrepancy becomes increasingly larger.

The upper half of FIG. 8 depicts the uniform region-to-region spacing employed in prior art spatial filters, corresponding to the linear graph 47 in FIG. 7. According to the invention, however, in the improved spatial filter, the region-to-region spacing is not uniform but increases according to curve 48 in FIG. 7. Thus, as shown in the lower half of FIG. 8, while the first few opaque regions in the filter are at approximately the same position as they would be for the linear case, if, for example, one moves outward, to the right, from the center of the filter, the discrepancy between the position of the regions in the linear filter and those in the non-linear filter becomes increasingly large. Again, it must be emphasized that for clarity, the scale has been greatly exaggerated.

Because the step-and-repeat spacing of typical integrated circuit devices varies from 20 to 120 mils, the typical spacing between the opaque regions on a spatial filter varies from 20 to 120 microns, assuming an HeNe laser and a 100 mm focal length lens. It is, therefore, essential that the filter be manufactured with the greatest care, and considerable accuracy is required to successively increase the distance between the regions, in accordance with Equation 2. Thus, if a spatial filter, constructed in accordance with Equation 2 and graph 48 of FIG. 7 is substituted for the spatial filter 23 in FIG. 1, the filter will effectively block all periodic information from the photomask 17, including the edge information, even though the dots are actually positioned on planar surface 45, rather than the actual back plane of lens 22. The instant invention, of course, does not fully compensate for the fact that light from the photomask is not completely focused on the spatial filter. However, this can be compensated for, if desired, by making the size of the regions for suppressing the higher spatial frequencies slightly larger than those for suppressing the lower spatial frequencies. From a practical standpoint, these requirements are so demanding that production of a spatial filter, according to this invention, can only be effected in a computer-assisted device, such as the PPG or a computer-controlled electron-beam machine.

One skilled in the art will appreciate that while the invention has been described with reference to the inspection of integrated circuit photomasks, it may also be used to inspect any workpiece having optical characteristics approximating those of an optical grating, either transmissive or reflected, e.g., a processed silicon semiconductor slice. For example, the invention has successfully been used to inspect fine metallic grids, and diode array targets, such as those used in the manufacture of Picturephone camera tubes, and the like. Further, if desired, the spatial filter might comprise a matrix of transparent regions on an opaque

field, rather than a matrix of opaque regions on a transparent field. In this latter event, periodic information would be transmitted, rather than blocked. Of course, the term "regions," as used herein, is intended to comprise various shapes, such as circles, squares, triangles, etc. The actual shape employed is merely a matter of convenience, provided that the corresponding light dot in the diffraction pattern is blocked. Also, various changes and substitutions may be made to the elements shown, without departing from the spirit and scope of the invention.

Finally, it must again be stressed, that while "Manhattan" geometry is by far the most common found in integrated circuits, the methods and apparatus of this invention may be used to inspect workpieces having any geometry in their features.

What is claimed is:

1. A method of isolating non-periodic errors in a two-dimensional pattern containing a regular array of nominally identical elements, mutually spaced apart along at least one axis by a predetermined distance, which comprises the steps of:

directing a spatially coherent beam of light at the pattern to diffract the light;

focusing the diffracted light on a filter consisting of a plurality of discrete substantially equally sized opaque regions on a transparent field, the spacing between adjacent regions, along at least one axis of the filter, increasing from region-to-region from the centermost region to the edges of the filter, to spatially modulate the light wherein the distance X of any given region, from said centermost region, along said at least one axis, is given by the formula:

$$X = f \tan [\sin^{-1} (n \lambda / d)]$$

where,

f = the focal length of the Fourier transforming lens;

λ = the wavelength of said beam;

n = the order of the spatial harmonic;

d = the step-and-repeat distance of said two-dimensional pattern; and

reimaging the spatially modulated light to form an image exhibiting the non-periodic errors in the pattern, said filter blocking essentially all periodic information in said image, including higher spatial frequency components.

2. Apparatus for inspecting non-periodic errors in a two-dimensional pattern containing a plurality of nominally identical and regularly spaced elements, arranged in a planar periodic array, which comprises:

means for directing a spatially coherent beam of light at the plane of the pattern so that the light is diffracted thereby;

a first lens positioned to focus the light diffracted by the pattern;

a planar optical filter consisting of distribution of discrete substantially equally sized opaque regions on a transparent field, the spacing between adjacent regions, along at least one axis of the filter, increasing from region-to-region from the centermost region to the edges of the filter,

wherein the distance X of any given region, on said at least one axis, from said centermost region is given by the formula:

$$X = f \tan [\sin^{-1} (n \lambda / d)]$$

where,

f = the focal length of the Fourier transforming lens;

λ = the wavelength of said beam;

n = the order of the spatial harmonic;

d = the step-and-repeat distance of said two-dimensional pattern; the filter being positioned at the focal plane of the first lens for spatially modulating the intensity of the light focused thereon by the first lens;

a second lens positioned to reimage the light transmitted by the filter to form a visual image of the non-periodic errors in the pattern of the image display means; and

means for projecting the visual image onto the image display means.

3. Apparatus according to claim 2 wherein said image display means and said projecting means comprises:

a television camera focused on said visual image; control means, connected to said camera, for supplying deflection signals and power to said camera, said camera scanning across said visual image to detect said non-periodic errors; and counting means, connected to the video output of

said camera, for counting the number of non-periodic errors so detected.

4. A spatial filter, which consists of:

a matrix-like array of discrete substantially equally sized opaque elements on a transparent field, the spacing between adjacent elements, along at least one axis of the array, increasing from element-to-element, from the centermost element outwards towards the edges of the array, wherein the distance X of any given element on said at least one axis, from said centermost element, is given by the formula:

$$X = f \tan [\sin^{-1} (n \lambda / d)]$$

wherein,

f = the focal length of the Fourier transforming lens;

λ = the wavelength of the light forming said image;

n = the order of the spatial harmonic;

d = the step-and-repeat distance of the workpiece; whereby, when said filter is positioned to intercept the Fourier transform of the image of a workpiece comprising a matrix-like array of nominally identical features, said opaque elements inhibit further transmission of substantially all periodic information in said transform.

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UNITED STATES PATENT OFFICE CERTIFICATE OF CORRECTION

Patent No. 3,738,752 Dated June 12, 1973

Inventor(s) R. A. HEINZ, R. C. OEHRLE, L. S. WATKINS, T. E. ZAVECZ

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

In the specification, Column 1, line 41, "effect" should read --effort--.

In the claims, Claim 2, column 8, line 54, "direcging" should read --directing--; line 59, "of distribution" should read --of a distribution--.

Signed and sealed this 26th day of March 1974.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents