

PATENT SPECIFICATION

(11) 1204 170

DRAWINGS ATTACHED

- (21) Application No. 35357/69 (22) Filed 13 Dec. 1967
(62) Divided Out of No. 1204169
(31) Convention Application No. 617349 (32) Filed 20 Feb. 1967 in
(33) United States of America (US)
(45) Complete Specification published 3 Sept. 1970
(51) International Classification G 02 b 27/38
(52) Index at acceptance G2J 33B



(54) METHOD OF FABRICATING A HOLOGRAM

(71) We TEXAS INSTRUMENTS INCORPORATED, a Corporation organized according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the fabrication of a hologram of the Fourier transform of an array of point sources of light. A hologram of this type can be used in the production of multiple images of a master image.

Multiple images for a micro-miniature circuit are usually produced on the semiconductor wafer by a system using a single image master. Each image in the pattern must be an accurate reproduction of the master image and precisely spaced with respect to the surrounding images. The two basic requirements for repetition of a circuit pattern are the achievement of high image quality and precise registration between each image.

Presently, the highest quality multiple image patterns are produced by using elaborate step-and-repeat cameras with lenses of high aperture to give the necessary resolving power. With the step-and-repeat camera, a multiple image mask is constructed, and the image pattern is transferred to a semiconductor wafer by the process of contact printing. To produce a 30-by-30 array on the mask, it is necessary to perform 900 exposures through the master image. For each of the 900 exposures, the master image must be positioned accurately within .0001 of an inch. Although the step-and-repeat camera produces the best results of previously available systems, it is a tedious, time-consuming and expensive way to produce multiple images.

Another system for producing multiple images is the pinhole array camera. A pinhole array camera system consists of a mask having an array of precisely positioned uniform diameter apertures. The resolution of the images formed by this system is controlled by the aperture size and the distance between the pinhole array and the light-sensitive surface on which the multiple images are formed. Since the effective lens quality of a pinhole opening is very poor, the images produced by this method are of a lower quality than the step-and-repeat camera system. However, the pinhole-array camera system is relatively simple and inexpensive.

Another desirable feature in multiple reproduction is the ability to produce intermixed arrays of several master images. Also, it is often desirable to produce complex patterns of a master image. The pinhole array camera system lacks the ability to produce intermixed multiple images from several patterns.

Co-pending Patent Application No. 56645/67 (Serial No. 1204169) describes apparatus for forming multiple images of a master image, which includes a hologram which is a Fourier transform of an array of point sources in positions corresponding to the positions of images in the multiple image array to be formed. The apparatus also includes optical means positioned to produce, on a light-sensitive element, the Fourier transform of the light output of the hologram when the hologram is illuminated by a monochromatic light source.

The present invention provides a method of fabricating a hologram of the Fourier transform of an array of point sources of light, including the step of exposing a recording medium to a reference wave and an object wave of monochromatic light simultaneously, one for each point source in the array of point sources, while

varying the relative angles of incidence of the reference wave and the object wave for each exposure such that the relative difference between the angles of the incidence of the reference wave and the object wave for each exposure corresponds to the relative differences in location of the point sources in the array.

A hologram formed in accordance with the invention may be utilized in apparatus for forming multiple images of a master image, for example apparatus of the type disclosed in the above-mentioned co-pending Application No. 56645/67 (Serial No. 1204169).

By way of example, a method in accordance with the invention will be described with reference to the accompanying drawings in which:

Figure 1 is a diagrammatic of a system for producing in a single step a multiple image pattern from a single image master; and

Figure 2 is a schematic of a system for generating a Fourier transform hologram.

Referring to Figure 1, there is shown a system for producing multiple images from one single-image master. The single-image master 10 is illuminated from a source of monochromatic light 11, for example, a laser. Light waves from the source 11 passing through the master image 10 produce a diffraction pattern, the Fourier transform of this pattern is established at a hologram 12 by means of a double convex lens 13. The complex light pattern from the master image 10 passes through the hologram 12 thereby producing another complex diffraction pattern; the Fourier transform of this second pattern is established at the photosensitive surface of a body, such as a semiconductor wafer 14, by means of a double convex lens 16.

With the relatively simple system shown in Figure 1, it is possible to produce in a single step process, multiple images on the photosensitive surface of the semiconductor wafer 14 from the master image 10. The focal-length of the convex lenses 13 and 16 determines the spacing between the various elements. For example, the distance between the master image 10 and the convex lens 13, and the distance between the hologram 12 and the convex lens 13, are determined by the focal lengths of the convex lens 13. Similarly, the distance between the hologram 12 and the convex lens 16, and the distance between the semiconductor wafer 14 and the convex lens 16 are determined by the focal lengths of the convex lens 16. The tolerances on the distances between the various elements are not critical.

In operation, consider that the master image 10 has a complex wave transmission function equal to $f(x',y')$, and that the master image is located on the focal plane $x'y'$ of the convex lens 13. If the hologram 12 is also located on a focal plane of the convex lens 13, identified as plane uv , then the lens 13 establishes the Fourier transform of the function $f(x',y')$ on the uv plane. From well known diffraction and Fourier transform theory, the amplitude of the light waves on the hologram will be:

$$F(u,v) = \mathcal{F}[f(x',y')] = \iint_{-\infty}^{\infty} f(x',y') e^{-\frac{i2\pi(ux'-vy')}{f_1\lambda}} dx'dy' \quad (1)$$

where f_1 is the focal length of the lens 13 and λ is the wave-length of the light from the source 11. If the hologram 12, located in the uv plane, has a transmission function $G(u,v)$ then the amplitude of the light wave passing through the hologram is equal to the product of $F(u,v)$ and $G(u,v)$. Since the uv plane is also a focal plane of the convex lens 16, the Fourier transform of the product of $F(u,v)$ and $G(u,v)$ will be established on the semiconductor wafer 14. The plane of the semiconductor wafer 14 is identified as being the xy plane and is at a focal-point of the convex lens 16. In mathematical terms, the light amplitude distribution on the xy plane is given by the equation:

$$h(x,y) = \iint_{-\infty}^{\infty} F(u,v) G(u,v) e^{-\frac{i2\pi}{f_2\lambda}(ux-vy)} du dv \quad (2)$$

where f_2 is the local length of the convex lens 16. According to the convolution theorem for Fourier transformation, the light amplitude distribution on the xy plane is given by the equation:

$$h(x, y) = \left[\iint_{-\infty}^{\infty} F(u, v) e^{\frac{-i2\pi(ux+vy)}{f_2\lambda}} du dv \right]^* \iint_{-\infty}^{\infty} g(u, v) e^{\frac{-i2\pi(ux+vy)}{f_2\lambda}} du dv \quad (3)$$

5 where the "*" is the convolution integral. The first integral in equation (3) is the mathematical representation of the pattern of the master image 10 modified by a magnification factor f_1/f_2 : 5

$$f(mx, my) = \iint_{-\infty}^{\infty} F(u, v) e^{\frac{-i2\pi(ux+vy)}{f_2\lambda}} du dv \quad (4)$$

where $m = -f_1/f_2$, the magnification factor.

10 Now if the function $g(x, y)$ is chosen to represent the Fourier transformation of $G(u, v)$ and $f(mx, my)$ represents the Fourier transformation of $F(u, v)$ from equation (1) then: 10

$$g(x, y) = \iint_{-\infty}^{\infty} G(u, v) e^{\frac{-i2\pi(ux+vy)}{f_2\lambda}} du dv \quad (5)$$

and equation (3) can be written as:

$$h(x, y) = f(mx, my)^* g(x, y) = \iint_{-\infty}^{\infty} f(mx'', my'') g(x-x'', y-y'') dx'' dy'' \quad (6)$$

Assume the Fourier transformation of the function $G(u, v)$ can be written as:

$$g(x, y) = \delta(x-a_p) \delta(y-b_q) \quad (7)$$

Then by substitution of equation (7) into equation (6) the function on the xy plane can be written as:

$$h(x, y) = \sum_{pq} f \left[m(x-a_p), m(y-b_q) \right] \quad (8)$$

where a_p is the distance along the x axis and b_q is the distance along the y axis. Equation (8) mathematically describes the original pattern on the master image 10 reduced and multiplied into an array by the hologram 12. The configuration of the array is described by the function $G(u,v)$; by varying the a_p and b_q terms any array can be generated.

Referring to Figure 2, there is shown a system for producing the hologram 12 of Figure 1 of an array of the Fourier transform of points corresponding in position with the array of images to be formed from the master image 10. Holograms have frequently been described as modulated diffraction gratings. In the usual method of forming a hologram, a diffraction pattern is formed on a photographic plate by the interference of a secondary wave with a reference wave. The interference pattern on the photographic plate bears no resemblance to the original object but contains substantially more information than a photograph. To the unaided eye, the image embodied in a hologram cannot be detected since the visible structure is purely extraneous and is the result of a somewhat less than perfect light transmitting system. In the case of a hologram of an array of points, the object can be an array of pinholes arranged in the desired pattern. However, a hologram made by interference of light waves passing through a pinhole array with a reference wave, will not produce high quality images.

In Figure 2, the hologram is produced by multiple exposure of a photographic plate for each image position to be registered on the photosensitive surface of the semiconductor wafer 14. The system of Figure 2 includes a laser light source 17 generating a laser beam partially reflected by a reflective surface 18 to a reflective surface 19. The laser beam from the surface 17, after reflection from the surface 19, is expanded by a beam expander 21 and collimated by a lens 22. The collimated light from the lens 22 is the reference wave required to generate an interference pattern on a photographic plate 23. Light passing through an aperture in the reflective surface 18 is transmitted to a reflective surface 24 and reflected therefrom to a wave expander 26. Light waves from the expander 26 are collimated by a lens 27 and reflected to the photographic plate 23 by means of an adjustable reflective surface 28.

In operation, the photographic plate 23 is exposed once for each image position desired on the semiconductor wafer 14. For each image position, the reference wave is maintained constant and the object wave varied by means of the adjustable reflective surface 28. Thus, to create the desired multiple image pattern, the adjustable reflective surface 28 is positioned for each exposure. To insure equal intensity images on the photosensitive surface of the semiconductor wafer 14, the same exposure time is used for each image position. Remarkably good image resolution is possible by the system of Figure 1 when using a hologram produced by the system of Figure 2.

This technique of hologram production is known as optical image synthesis which can be shown mathematically; assume the reference wave is defined as:

$$R_w = A_o e^{-i2\pi cu/f_2 \lambda} \quad (9)$$

where A_o is the amplitude of the reference wave and cu is the position of the reference beam with respect to the uv plane. Also, assume that the object wave is given by the following equation:

$$O_w = A_i e^{-i2\pi(a_p u + b_q v)/f \lambda} \quad (10)$$

where A_i is the amplitude of the object wave. The amplitude of the interference pattern recorded on the photographic plate 23, for each exposure, is equal to the sum of the equations 9 and 10, and is written as follows:

$$A_{pq} = A_o e^{\frac{-i2\pi cu}{f_2 \lambda}} + A_i e^{\frac{-i2\pi(a_p u + b_q v)}{f \lambda}}$$

(11)

The amplitude transmission is given by the equation:

$$T(uv) = \alpha + \alpha_2 \left[\sum_{pq} e^{-\frac{i2\pi}{f_2\lambda}} C_{pq} e^{-\frac{i2\pi}{f_2\lambda} (a_p u + b_q v)} + c.c. \right] \quad (12)$$

where α_1 and α_2 are constants, c.c. is the complex conjugate of $e^{-\frac{i2\pi}{f_2\lambda} (a_p u + b_q v)}$ and all the remaining terms have been described previously. The direction of the object wave for each image positioned as it interferes on the photographic plate 23 is given by the terms a_p/f_2 and b_q/f_2 of equation 12; where a_p/f_2 is an angle in the uw plane and b_q/f_2 is an angle in the vw plane, as shown in Figure 2.

WHAT WE CLAIM IS:—

1. A method of fabricating a hologram of the Fourier transform of an array of point sources of light, including the steps of exposing a recording medium to a reference wave and an object wave of monochromatic light simultaneously, once for each point source in the array of point sources, while varying the relative angles of incidence of the reference wave and the object wave for each exposure such that the relative difference between the angles of the incidence of the reference wave and the object wave for each exposure corresponds to the relative differences in location of the point sources in the array.
2. A method as set forth in claim 1, wherein the reference wave and the object wave of monochromatic light are formed by passing a monochromatic light beam through a beam splitter.
3. A method as set forth in claim 1 or claim 2, wherein the reference wave and the object wave are directed onto the recording medium by directing the object wave upon a reflecting surface, directing the reference wave and the reflected object wave onto the recording medium to form a first interference pattern thereon, recording the first interference pattern on the recording medium, thereby to form upon the recording medium the Fourier transform of a first one of the point sources in the array of point sources, and adjusting the angle of the reflecting surface with respect to the object wave by an amount corresponding to the separation of the next point source to be formed from the first formed point source, thereafter directing the object wave upon the adjusted reflecting surface, directing the reference wave and the adjusted reflected object wave onto the recording medium to form a second interference pattern on the recording medium, and recording the second interference pattern on the recording medium, thereby to form upon the recording medium the Fourier transform of a second one of the point sources in the array of point sources.
4. A method as set forth in claim 3, further including repeating the sequence of steps beginning with the adjustment of the angle of the reflecting surface with respect to the object wave for each additional point source in the array of point sources.
5. A method of fabricating a hologram of the Fourier transform of an array of point sources of light, substantially as described herein with reference to Figure 2 of the accompanying drawings.
6. A hologram fabricated by a method as set forth in any one of the preceding claims.

ABEL & IMRAY
Chartered Patent Agents,
Quality House,
Quality Court,
Chancery Lane,
London, W.C.2.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1970.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

The amplitude transmission is given by the equation:

$$T(uv) = \alpha + \alpha_2 \left[\sum_{pq} e^{-i2\pi \frac{pq}{f_2 \lambda}} c u e^{-i2\pi \frac{pq}{f_2 \lambda} (a_p u + b_q v)} + c.c. \right] \quad (12)$$

where α_1 and α_2 are constants, c.c. is the complex conjugate of $e^{-i2\pi \frac{pq}{f_2 \lambda} (a_p u + b_q v)}$ and all the remaining terms have been described previously. The direction of the object wave for each image positioned as it interferes on the photographic plate 23 is given by the terms a_p/f_2 and b_q/f_2 of equation 12; where a_p/f_2 is an angle in the uw plane and b_q/f_2 is an angle in the vw plane, as shown in Figure 2.

WHAT WE CLAIM IS:—

1. A method of fabricating a hologram of the Fourier transform of an array of point sources of light, including the steps of exposing a recording medium to a reference wave and an object wave of monochromatic light simultaneously, once for each point source in the array of point sources, while varying the relative angles of incidence of the reference wave and the object wave for each exposure such that the relative difference between the angles of the incidence of the reference wave and the object wave for each exposure corresponds to the relative differences in location of the point sources in the array.
2. A method as set forth in claim 1, wherein the reference wave and the object wave of monochromatic light are formed by passing a monochromatic light beam through a beam splitter.
3. A method as set forth in claim 1 or claim 2, wherein the reference wave and the object wave are directed onto the recording medium by directing the object wave upon a reflecting surface, directing the reference wave and the reflected object wave onto the recording medium to form a first interference pattern thereon, recording the first interference pattern on the recording medium, thereby to form upon the recording medium the Fourier transform of a first one of the point sources in the array of point sources, and adjusting the angle of the reflecting surface with respect to the object wave by an amount corresponding to the separation of the next point source to be formed from the first formed point source, thereafter directing the object wave upon the adjusted reflecting surface, directing the reference wave and the adjusted reflected object wave onto the recording medium to form a second interference pattern on the recording medium, and recording the second interference pattern on the recording medium, thereby to form upon the recording medium the Fourier transform of a second one of the point sources in the array of point sources.
4. A method as set forth in claim 3, further including repeating the sequence of steps beginning with the adjustment of the angle of the reflecting surface with respect to the object wave for each additional point source in the array of point sources.
5. A method of fabricating a hologram of the Fourier transform of an array of point sources of light, substantially as described herein with reference to Figure 2 of the accompanying drawings.
6. A hologram fabricated by a method as set forth in any one of the preceding claims.

ABEL & IMRAY
Chartered Patent Agents,
Quality House,
Quality Court,
Chancery Lane,
London, W.C.2.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1970.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

