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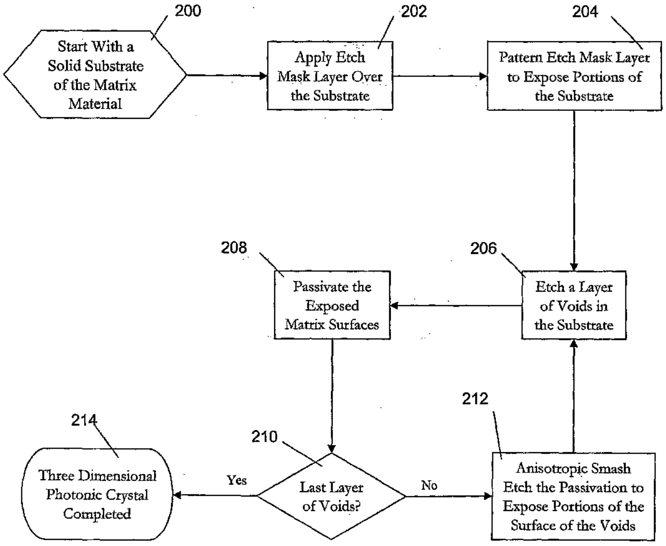
(54) Title: METHOD FOR FABRICATING THREE-DIMENSIONAL PHOTONIC CRYSTALS USING A SINGLE PLANAR ETCH MASK AND DEEP REACTIVE-ION/PLASMA ETCHING



(57) Abstract: A three dimensional photonic crystal including a matrix formed of a contiguous solid material and method of manufacturing. The matrix surrounds a plurality of substantially spherical voids. The voids are arranged in a predetermined pattern which forms a plurality of planar layers. These plurality of layers are stacked so that the voids in each layer are aligned to form vertical columns with voids from at least a subset of the other layers. The voids in each vertical column have openings between adjacent voids in the column.

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METHOD FOR FABRICATING THREE-DIMENSIONAL PHOTONIC CRYSTALS USING A SINGLE PLANAR ETCH MASK AND DEEP REACTIVE-ION/PLASMA ETCHING

The present invention concerns a design for producing three-dimensional photonic crystals.

Photonic crystals, periodic dielectric, or possibly metallic, structures with periodicities comparable to the wavelength of light, have many unique properties. Photonic crystals are of great interest in the field of photonics because certain types of photonic crystals exhibit a photonic bandgap. The photonic bandgap defines a range of frequencies at which electromagnetic waves are not permitted to propagate. Additionally, frequencies outside the bandgap that are allowed to propagate do so with unique and useful dispersion properties, including self-collimation, negative refraction, and superprism effect.

Different types of photonic crystals are proposed and tabulated on page 862 in Baba, "Semiconductor Micro Resonators and Control of Natural Emission", Solid State Physics (Japanese), vol. 32, No. 11, 1997, pages 859-869.

The typical photonic crystal is a spatially periodic structure. This spatially periodic structure may be one, two, or three-dimensional. One well-known photonic crystal exhibits two-dimensional periodicity in which multiple elongated, e.g. cylindrical, elements made of a dielectric material are in a two-dimensional periodic pattern with their longitudinal axes parallel to each other.

Joannopoulos et al., "Molding the Flow of Light" Photonic Crystals pages 124-125, discuss the case of elongated elements in the form of air columns in dielectric along with a photonic bandgap map for a triangular lattice of air columns drilled in a dielectric medium having permittivity 11.4. Figure 4 on page 125 of Joannopoulos et al. illustrates this photonic bandgap map.

Joannopoulos et al. also consider "honeycomb lattice" along with a photonic bandgap map for this structure. This photonic bandgap map is presented in Figure 5 on page 125 of Joannopoulos et al.

Referring to Joannopoulos et al.'s Figure 4, the photonic bandgap map for two dimensional triangular lattice of air columns clearly indicates that for r/a around 0.45, the triangular lattice of air columns possesses a complete band gap for TE polarization and TM polarization for frequencies around $0.45(2\pi c/a)$, where r is a radius of air column, a is a lattice constant, c is the speed of light. A complete band gap of the triangular lattice of air columns occurs at a diameter of $d=0.95a$, at a midgap frequency of $\omega a/2\pi c=0.48$, where ω is angular frequency. Thus, this structure has very thin dielectric veins of width 0.05a between the air columns. To fabricate such a structure with a photonic bandgap at a standard optical communications wavelength, $\lambda=1.5$ μm, requires a minimum feature size of 0.035 μm. Such fine feature size may be fabricated, but this is very difficult.

The formation of structures with such small feature sizes in three dimensions has proven even more difficult.

SUMMARY OF THE INVENTION

The present invention provides an exemplary method to form three-dimensional (3D) photonic crystal structures using conventional planar silicon micromachining technology. The method utilizes a single planar etch mask coupled with time multiplexed sidewall passivating deep anisotropic reactive ion etching along with isotropic etch process to create three-dimensional photonic crystal devices. In the process, anisotropic etching is followed by isotropic etching leading to the formation of sphere like voids. This step is followed by sidewall polymer deposition and local removal of the polymer from the bottom of the spheres that allows the etch process to be repeated and produce many layers.

For the etch mask initially patterned with a square lattice, the etch sequence methodology explained above yields a 3D structure with simple cubic symmetry. Theoretical calculations predict that this structure possesses a complete photonic band gap. Optimization of the photonic band gap or other optical dispersion properties, as applications demand, can be achieved by using different lattices (square, triangular, hexagonal) as the etch mask to produce photonic crystals with different crystalline structures. Further, by utilizing this fabrication scheme, photonic crystals over a wide range of the electromagnetic spectrum (<3Thz to >300Thz) can be fabricated by scaling the etch times and the mask dimensions.

There is also provided according to this invention a method for fabricating three-dimensional (3D) photonic crystal structures comprising

a matrix formed of a contiguous solid material, the matrix surrounding a plurality of substantially spherical voids, the voids arranged in a predetermined pattern forming a plurality of planar layers, the plurality of layers stacked so that the voids in each layer are aligned to form vertical columns with voids from at least a subset of the other layers, the voids in each vertical column having openings between adjacent voids in the column.

The method for manufacturing such three dimensional photonic crystal including a plurality of voids, comprises the steps of:

a) providing a substrate;

b) applying an etch mask layer to the substrate;

c) patterning the etch mask layer to form a patterned etch mask layer including a plurality of holes;

d) etching a top layer of voids in the substrate corresponding to the plurality of holes in the patterned etch mask layer;

e) forming a passivation layer on the surface of the top layer of voids;

f) anisotropic etching a plurality of openings in the passivation layer corresponding to the plurality of holes in the patterned etch mask layer;

g) etching a second layer of voids in the substrate corresponding to the plurality of openings in the passivation layer; and

h) repeating steps (e), (f), (g), and (h) until the three dimensional photonic crystal structure is complete.

There is also provided according to this invention a method for manufacturing a three dimensional photonic crystal including a plurality of voids, the method comprising the steps of:

a) providing a substrate;

b) applying an etch mask layer to the substrate;

c) grayscale patterning the etch mask layer to form a grayscale etch mask including a first plurality of holes and a second plurality of holes, the second plurality of hole extending less than completely through the grayscale etch mask;

d) anisotropically etching a plurality of pilot holes in the substrate corresponding to the first plurality of holes in the patterned etch mask layer;

e) forming a passivation layer on the surface of the pilot holes and the grayscale etch mask;

f) anisotropically etching a plurality of openings in the passivation layer corresponding to the first plurality of holes and the second plurality of holes;

g) anisotropically etching the second plurality of holes to completely extend through the grayscale etch mask;

h) etching a plurality of offset layers of voids in the substrate, a first offset layer corresponding to the first plurality of holes in the grayscale etch mask and a second offset layer corresponding to the second plurality of holes in the grayscale etch mask;

i) anisotropically etching a plurality of depressions in the surface of the plurality of voids corresponding to the first plurality of holes and the second plurality of holes in the grayscale etch mask;

j) forming a passivation layer on the surface of the voids;

k) anisotropic etching a plurality of openings in the passivation layer corresponding to the plurality of depressions in the surface of the plurality of voids; and

l) repeating steps (h), (i), (j), (k) and (l) until the three dimensional photonic crystal structure is complete.

BRIEF DESCRIPTION OF THE FIGURES

The invention is best understood from the following detailed description when read in connection with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawing are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawing are the following figures:

Figure 1 is a perspective drawing of a unit cell of exemplary simple cubic lattice three-dimensional photonic crystal according to the present invention.

Figure 2 is a flowchart illustrating an exemplary method of manufacture of the exemplary simple cubic lattice three-dimensional photonic crystal of Figure 1.

Figures 3A-H are side plan cutaway drawings of an exemplary simple cubic lattice three-dimensional photonic crystal during manufacture according to the flowchart of Figure 2.

Figure 4 is a perspective drawing of a unit cell of exemplary body centered cubic (BCC) lattice three-dimensional photonic crystal according to the present invention.

Figure 5 is a flowchart illustrating an exemplary method of manufacture of the exemplary BCC lattice three-dimensional photonic crystal of Figure 4.

Figures 6A-3H are side plan cutaway drawings of an exemplary BCC lattice three-dimensional photonic crystal during manufacture according to the flowchart of Figure 5.

Figure 7 is a scanning electron microscope image showing a silicon photonic crystal etched with 2 layers of roughly spherical voids according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 is a three-dimensional rendering of a unit cell of exemplary simple cubic lattice three-dimensional photonic crystal 100. The structure repeats itself along all three Cartesian directions. The structure includes substrate material 102 and voids 104. In this structure, voids 104 mimic the structure of atoms within a crystal. Such structures are of great interest due to their unique optical properties, but have been difficult to form. Theoretical calculations, described by H.S. Sözüer and J.W. Haus in "Photonic Bands: Simple Cubic Lattice," J. Opt. Soc. Am. B 10(2), 296 (1993), predict that this structure should possess a complete photonic band gap. These three dimensional photonic crystals may form optical materials analogous to electrical semiconductors. With proper design of defects, such as missing or differently sized voids periodically spaced within the photonic crystal structure, optical material analogous to doped semiconductors and/or semiconductor electronic devices may be formed.

Substrate material 102 may be any solid material, although it is desirably an optical dielectric, such as glass, quartz, sapphire, and silicon. Metal substrate materials may also form photonic crystals as described in US Patent 6,274,293, Method Of Manufacturing Flexible Metallic Photonic Band Gap Structures, And Structures Resulting Therefrom, to Gupta, et al. Voids 104 may desirably be air filled voids or may be totally or partially filled with a dielectric having a different index of refraction than the substrate, such as: polymers of triflouromethane, perfluorinated styrene-like monomers, or ether-like fluorine compounds; photoresist; optical epoxy; silicon dioxide; silicon nitrate; or material of the same material family as the substrate material, for example InP grown in a substrate of AlGaAsP. Additionally, the voids may be filled or coated with a metal.

Figure 2 is a flowchart that provides an overview of an exemplary method of forming exemplary simple cubic lattice three-dimensional photonic crystal 100 of Figure 1. This exemplary method is based on a combination of strongly anisotropic and weakly anisotropic etching of silicon using inductively coupled plasma (ICP) etching through an etch mask that has been patterned with a two-dimensional array of holes. It is understood by one skilled in the art that this exemplary method is not limiting. For example, other combinations of anisotropic and weakly anisotropic, or isotropic, etching techniques may be used, such as laser drilling (anisotropic) coupling with a weakly anisotropic wet chemical etch. Additionally, as described above with reference to Figure 1, silicon is only one of many possible substrate materials.

One advantage of this exemplary technique arises from the use of a planar (two-dimensional) etch mask and single cyclic etching process to achieve three-dimensional structures. Other methods for three-dimensional photonic-crystal fabrication suffer from far greater complexity; for example, self-assembled arrangements of colloidal particles of silica or polystyrene tend to contain many defects, have low refractive index contrast, and require long process times for fabrication. Interferometric/holographic lithography also suffers from low refractive index contrast; the conventional method to overcome low-index contrast is backfilling structures with high-index material, e.g. by liquid phase chemical vapor deposition, sol-gel infiltration, etc. This adds complexity, cost, and time to the processes and increases the likelihood of defects. Layer-by-layer processes typically require numerous time-consuming patterning, deposition, and etching processes, each of which must be precisely aligned and typically carried out in a number of different instruments. The present invention realizes high-quality photonic-crystal structures directly in high-index material in a short period of time (etch cycles using ICP may desirably take less than an hour, or even a minute) potentially using a single machine. It also utilizes very mature two dimensional/planar lithographic methods for the fabrication of the etch mask. In addition, this etching process should be applicable to the fabrication of photonic crystals over a range of length scales, for applications over a wide range of the electromagnetic spectrum (<3 THz to >30 THz), with minimal modification other than scaling the etch times and mask dimensions.

Another advantage of this method of photonic-crystal fabrication is the ability to etch sphere-like voids which are sufficiently large so as to overlap, perforating the side membranes that would otherwise separate them, as shown in Figure 1. In the exemplary method of Figure 2, this sphere etch may be described as "isotropic," although it is in practice often weakly anisotropic. This structure desirably enhances the photonic bandgap.

The exemplary method of Figure 2 begins with solid substrate 300 of the matrix material, step 200. Etch mask layer 302 is applied over substrate 300, step 202. Etch mask layer 302 can be applied as in any number of standard lithographic methods such as spin-coating, evaporation, sputtering, or thermal oxidation, and can be formed from standard lithographic materials, including photoresist, e-beam resist, oxide or metal. Figure 3A shows a cut-away side view of the structure at this point in manufacture.

The etch mask layer is patterned and etched, step 204, to form patterned etch mask layer 304, as shown in Figure 3B. The etch mask layer may be patterned and etched using any standard lithographic methods, such as UV photolithography or electron beam (e-beam) lithography. The etch mask layer may be desirably patterned with a square pattern of holes to yield a three dimensional photonic crystal structure with a simple cubic lattice, as depicted in Figure 1. Alternatively, other tiling shapes, such as hexagons, parallelograms, triangles, or "Escher fish," may be used to form the pattern of holes patterned etch mask layer 304 to yield an exemplary three dimensional photonic crystal with a lattice having planes of voids, with each plane of voids arranged according to the tiling pattern.

Patterns including defects, possibly periodically spaced, may be used to introduce vertical line defects in the lattice structure of the exemplary three-dimensional photonic crystal, as well. These vertical line defects may be used to form waveguides through the substrate from top to bottom. Alternatively, a series of these vertical line defects may be arranged to form a waveguide for guiding light parallel to the top and bottom surfaces of the photonic crystal. Defects may desirably be formed by omitting holes in the pattern.

Once patterned etch mask layer 304 is formed, patterned top layer 303 of the voids is etched, step 206, forming single layer photonic crystal 306. This layer of voids is desirably etched using a weakly anisotropic ICP etch. ICP etching is desired because of the ability of ICP to provide either a strongly anisotropic or a weakly anisotropic etch by controlling the various process parameters, such as chemical mix used to creates the plasma, the chamber pressure, and the acceleration voltage. This allows both types of etching to be done without removing the substrate from the etching chamber. It is also noted that the ICP process parameters may be controlled such that an intermediately anisotropic etch may be performed, resulting in ellipsoidal voids. Ellipsoidal voids may be desirable to form an exemplary three-dimensional photonic crystal having an orthorhombic lattice structure. Additionally, ICP may be used to apply passivation layers between etch steps, by controlling the process parameters. Figure 3C illustrates the exemplary photonic crystal at the point in the manufacture.

Next, passivation layer 308 is formed on the exposed surfaces of single layer photonic crystal 306, step 208, as shown in Figure 3D. Passivation layer 308 may also cover the exposed surfaces of patterned etch mask layer 304, as shown in Figure 3D, or not, depending on the materials for these layers.

Desirably, this passivation layer is formed by polymerization of the ICP plasma material on these surfaces. Other thin coating methods may be used the form passivation layer 308.

The process is checked to determine if the layer of voids just formed is the final layer of the desired photonic crystal structure, step 210. If this is the final layer of voids desired to be formed in the photonic crystal structure, then the exemplary three-dimensional photonic crystal fabrication is complete, step 214. Otherwise, openings 310 are anisotropically "smash" etched into passivation layer 308, step 212. Desirably, the smash etch may be performed using ICP etching. Openings 310 desirably expose, but do not etch, the surface of single photonic crystal 306 directly below the holes in patterned etch mask layer 304, as shown in Figure 3E. It is noted that passivation layer 308 may be removed from the top surface of patterned etch mask layer 304, although this is not shown in Figure 3E.

Step 206 is then repeated to etch second layer 314 of voids, forming two layer photonic crystal 312, as shown in Figure 3F. Steps 208 and 210 are then repeated, as shown in Figure 3G. Figure 3H shows the exemplary process following one more smash etch, step 212.

The cycle of steps 212, 206, 208 and 210 is continued until the photonic crystal fabrication is completed. This allows the etch cycle to be repeated to produce many layers. In this sense, the exemplary method of Figure 2 is similar to a deep reactive-ion etching process developed for etching high-aspect-ratio features with vertical side walls known as Bosch etching. Bosch etching is described in US Patent 5,501,893. This etch sequence desirably yields a 3D structure with simple cubic symmetry, as shown in Figure 1, assuming the mask is patterned with a square lattice initially.

It is noted that the query of step 210 may occur before passivation layer 308 is applied in step 208. Also, additional steps including removing any remaining portions of passivation layer 308 from within the voids, removing patterned etch mask layer 304, applying a metal coating to the surfaces of the voids, and/or backfilling the voids with a dielectric or metal may be included between steps 210 and 214 of the exemplary method.

A preferred ICP system, SAMCO RIE-200IP, consists of load lock and wafer loader unit, ICP electronics and a process chamber. The plasma is inductively coupled at 13.56MHz via the matching unit and coil assembly into an alumina chamber. This enables high-density plasma capable of operating in a wide process range. 13.56 MHz RF biasing of the electrode via automatic power control and impedance matching provides independent energy control. Process gas is introduced to the chamber through the upper over assembly.

The wafers are placed on the electrode assembly, which is powered at 13.56 MHz. The wafer temperature is maintained at 15°C via temperature controlled, pressurized helium supplied to the back of the wafer, which are electrostatically clamped to the platen electrode. The system is equipped with an automatic pressure control (APC) valve, which can operate in one of two modes.

In automatic APC mode, the APC valve adjusts position to maintain the chamber pressure at a pre-determined value. In fixed APC mode, the APC position remains constant and the chamber pressure is a function of gas flows and RF power. The latter mode achieves very fast switching of gases enabling very high etch rates.

It should also be noted that there are several modifications to the process described above that would not depart from the spirit of the invention. It is possible to use similar processes to fabricate photonic crystals in materials other than silicon, and the etching system need not be an ICP method. Defects may be introduced into the 3D photonic crystal by patterning them into the etch mask, e.g. by leaving out or enlarging a single hole or a row of holes, or by superimposing additional structures. Planar defects could also be introduced by modifying one or more of the etch cycles to produce a layer or layers of smaller, larger, or differently shaped voids. Different lattices (square, triangular, hexagonal) can be used for the etch mask to produce photonic crystals with different crystalline structures.

Figure 4 is a three dimensional rendering of a unit cell of exemplary body centered cubic (BCC) lattice three-dimensional photonic crystal 400. The structure repeats itself along all three Cartesian directions. The structure includes substrate material 402 and voids 404. This structure is similar to the structure of exemplary simple cubic lattice three-dimensional photonic crystal 100 shown in Figure 1. Only the lattice structure is different.

The lattice structure of exemplary BCC lattice three dimensional photonic crystal 400 includes pairs of planes in which the spherical voids are offset from one another, while spherical voids of each plane in the lattice structure of exemplary simple cubic lattice three dimensional photonic crystal 100 are aligned. Therefore, exemplary BCC lattice three-dimensional photonic crystal 400 may not be formed using the exemplary method of Figure 2. The similar exemplary method of Figure 5 also uses a combination of strongly anisotropic and weakly anisotropic etching of silicon, as well as grayscale patterning of the etch mask layer. Desirably, ICP etching through the etch mask is used in the exemplary method of Figure 5, as in the exemplary method of Figure 2.

Even thought the exemplary method of Figure 5 is more complex than the exemplary method of Figure 2, it still includes the advantage of using of a planar (two-dimensional) etch mask and single cyclic etching process to achieve three dimensional structures. It also is still possible to utilize very mature two dimensional/planar lithographic methods for the fabrication of the etch mask in this exemplary method. It may be understood by one skilled in the art that this exemplary method may be used to form photonic crystals having different lattice structures that involve a set of two, or more, planes in which patterns of the voids are different and offset from the other planes in the set, such as monoclinic.

The exemplary method of Figure 5 begins with solid substrate 300 of the matrix material, step 500. Etch mask layer 302 is applied over substrate 300, step 502. Figure 6A shows a cut-away side view of the structure at this point in manufacture.

The etch mask layer is grayscale patterned and etched, step 504, so that some holes 601 in etch mask layer 302 are etched all the way to the surface of substrate 300 and some are etched approximately half way. These two sets of holes correspond to the desired locations of voids in the alternating offset layers of photonic crystal lattice structure. (In an alternative exemplary method in which the lattice structure includes three offset layers before repeating, the grayscale pattern includes two intermediate depth hole sets.) This forms grayscale patterned etch mask layer 600, as shown in Figure 6B. The etch mask layer may patterned and etched using any standard lithographic methods for forming an etch mask having multiple thickness regions.

Patterns including defects, possibly periodically spaced holes missing from the pattern, may be used in one or more of the grayscale levels to introduce a defect in the corresponding layers of voids.

Once patterned etch mask layer 600 is formed, pilot-holes 606 are etched, step 506, leaving drilled substrate 602. This anisotropic etch also reduces the thickness of grayscale patterned etch mask 600, to form thin grayscale etch mask 604, as shown in Figure 6C. Alternatively this etch step may etch away all of the etch mask material in non-pilot-hole holes 605, exposing the surface of drilled substrate 602 in these areas. In this alternative embodiment, patterned etch mask 610 (shown in Figure 6E at a later step in the fabrication process) is formed instead of grayscale etch mask 604.

Next, passivation layer 608 is formed on the exposed surfaces of drilled substrate 602 and grayscale etch mask 604 (or patterned etch mask 610), step 508, as shown in Figure 6D. Desirably, this passivation layer is formed by polymerization of the ICP plasma material on these surfaces.

Openings 612 are anisotropically "smash" etched into passivation layer 608, step 510. Desirably, the smash etch may be performed using ICP etching. Openings 612 desirably expose, but do not etch, the surface of drilled substrate 602 directly below the holes in patterned etch mask 610 and at the bottoms of pilot holes 606, as shown in Figure 6E. It is noted that passivation layer 308 is also desirably removed from the top surface of patterned etch mask 610, as shown in Figure 6E.

Next, offset layers of voids 616 are etched in drilled substrate 602, step 512, to form photonic crystal structure 614. These layers of voids are desirably etched using a weakly anisotropic ICP etch. Figure 6F illustrates the exemplary photonic crystal at the point in the manufacture.

The process is checked to determine if the offset layers of voids just formed are the final offset layers of the desired photonic crystal structure, step 514. If this is the final set of offset layers of voids desired to be formed in the photonic crystal structure, then the exemplary three dimensional photonic crystal fabrication is complete, step 522. Otherwise, depressions 618 are anisotropic "smash" etched into bottom surfaces of the voids directly below holes in the patterned etch mask 610, step 516, as shown in Figure 6G. Desirably, the smash etch may be performed using ICP etching. Depressions 618 desirably mark the starting point for the voids in the next set of offset layers.

Next, passivation layer 608 is formed on the exposed surfaces of photonic crystal structure 614, step 518, as shown in Figure 6H. Passivation layer 608 desirably also covers the exposed surfaces of patterned etch mask 610, as shown in Figure 6H.

Openings are anisotropically "smash" etched into passivation layer 608, desirably exposing, but do not etching, the surface of photonic crystal structure

614 in depressions 618. It is noted that passivation layer 308 is also desirably removed from the top surface of patterned etch mask 610.

Step 512 is then repeated to etch second set of offset layers of voids. Step 514 is then repeated to determine if the exemplary three-dimensional photonic crystal is complete.

The cycle of steps 516, 518, 520, 512 and 514 is continued until the photonic crystal fabrication is completed. This allows the etch cycle to be repeated to produce many sets of layers.

It is noted that additional steps including removing any remaining portions of passivation layer 608 from within the voids, removing patterned etch mask 610, applying a metal coating to the surfaces of the voids, and/or backfilling the voids with a dielectric or metal may be included between steps 514 and 522 of the exemplary method.

Figure 7 illustrates preliminary experimental results of exemplary embodiments of the present invention. This figure is a scanning electron microscope image showing a silicon sample etched with 2 layers of roughly spherical voids. The membranes between adjacent voids are clearly perforated, which is desirable for a photonic band gap.

Although the embodiments of the invention described above have been in terms of specific embodiments, it is contemplated that similar concepts may be practiced with other three dimensional photonic chip structures. Also, it may be understood by one skilled in the art that a number of other modifications exist which do not deviate from the scope of the present invention as defined by the appended claims.

CLAIMS

What is Claimed:

1. A three-dimensional photonic crystal structure comprising:

a matrix formed of a contiguous solid material;

wherein;

the matrix surrounds a plurality of substantially spherical voids arranged in a predetermined pattern forming a plurality of planar layers of voids;

the plurality of layers are stacked so that the voids in each layer are aligned to form vertical columns with voids from at least a subset of the other layers; and

the voids in each vertical column have openings between adjacent voids in the column.

2. The three-dimensional photonic crystal structure according to claim 1, wherein the predetermined pattern of substantially spherical voids is one of:

a simple cubic pattern;
a face centered cubic pattern; or
a body center cubic pattern.

3. The three-dimensional photonic crystal structure according to claim 1, wherein the contiguous solid material is one of an optical dielectric, glass, quartz, sapphire, silicon, AlGaAsP, or a metal.

4. The three-dimensional photonic crystal structure according to claim 1, wherein a surface of the matrix formed of the contiguous solid material surrounding the substantially spherical voids is coated with a coating material having an index of refraction different from the index of refraction of the contiguous solid material.

5. The three-dimensional photonic crystal structure according to claim 4, wherein the coating material is one of:

a polymer of triflouromethane;
a polymer of a perfluorinated styrene-like monomer;
a polymer of an ether-like fluorine compound;
photoresist;
optical epoxy;
silicon dioxide;
silicon nitrate; or
InP.

6. The three-dimensional photonic crystal structure according to claim 1, wherein the plurality of the substantially spherical voids filled with a fill material having an index of refraction different from the index of refraction of the contiguous solid material.

7. The three-dimensional photonic crystal structure according to claim 6, wherein the fill material is one of:

a polymer of triflouromethane;
a polymer of a perfluorinated styrene-like monomer;
a polymer of an ether-like fluorine compound;
photoresist;
optical epoxy;
silicon dioxide;
silicon nitrate; or
InP.

8. A method of manufacturing a three dimensional photonic crystal that includes a plurality of voids, the method comprising the steps of:

a) providing a substrate;

b) applying an etch mask layer to the substrate;

c) patterning the etch mask layer to form a patterned etch mask layer including a plurality of holes;

d) etching a top layer of voids in the substrate corresponding to the plurality of holes in the patterned etch mask layer;

e) forming a passivation layer on the surface of the top layer of voids;

f) anisotropically etching a plurality of openings in the passivation layer corresponding to the plurality of holes in the patterned etch mask layer;

g) etching a second layer of voids in the substrate corresponding to the plurality of openings in the passivation layer; and

h) repeating steps (e), (f), (g), and (h) until the three dimensional photonic crystal structure is complete.

9. The method according to claim 8, further comprising the step of:

i) filling the voids etched in steps (d) and (g) with a fill material having a different index of refraction than the substrate.

10. A method of manufacturing a three dimensional photonic crystal that includes a plurality of voids, the method comprising the steps of:

a) providing a substrate;

b) applying an etch mask layer to the substrate;

c) grayscale patterning the etch mask layer to form a grayscale etch mask including a first plurality of holes and a second plurality of holes, the second plurality of hole extending less than completely through the grayscale etch mask;

d) anisotropically etching a plurality of pilot holes in the substrate corresponding to the first plurality of holes in the patterned etch mask layer;

e) forming a passivation layer on the surface of the pilot holes and the grayscale etch mask;

f) anisotropically etching a plurality of openings in the passivation layer corresponding to the first plurality of holes and the second plurality of holes;

g) anisotropically etching the second plurality of holes to completely extend through the grayscale etch mask;

h) etching a plurality of offset layers of voids in the substrate, a first offset layer corresponding to the first plurality of holes in the grayscale etch mask and a second offset layer corresponding to the second plurality of holes in the grayscale etch mask;

i) anisotropically etching a plurality of depressions in the surface of the plurality of voids corresponding to the first plurality of holes and the second plurality of holes in the grayscale etch mask;

j) forming a passivation layer on the surface of the voids;

k) anisotropically etching a plurality of openings in the passivation layer corresponding to the plurality of depressions in the surface of the plurality of voids; and

l) repeating steps (h), (i), (j), (k) and (l) until the three dimensional photonic crystal structure is complete.

11. The method according to claim 10, further comprising the step of:

m) filling the voids etched in step (h) with a fill material having a different index of refraction than the substrate.

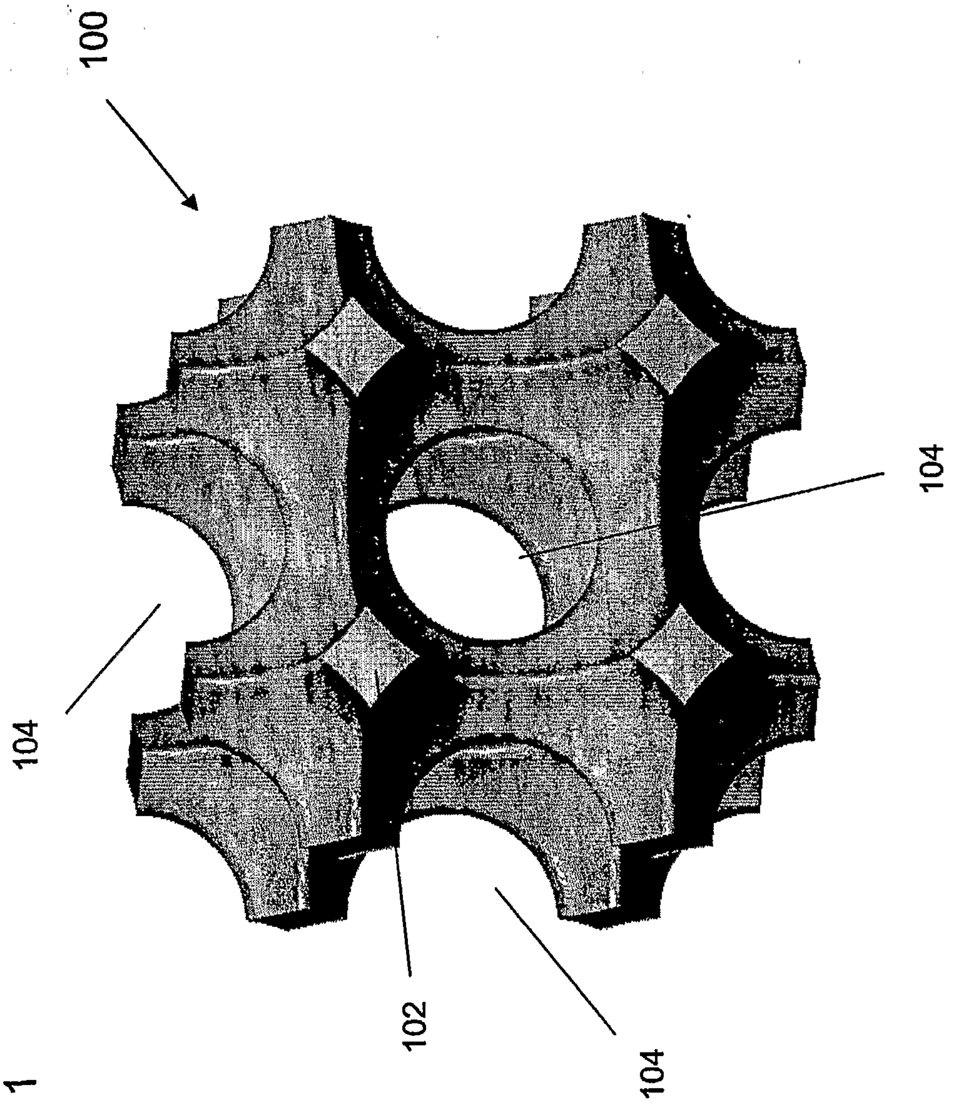


FIG. 1

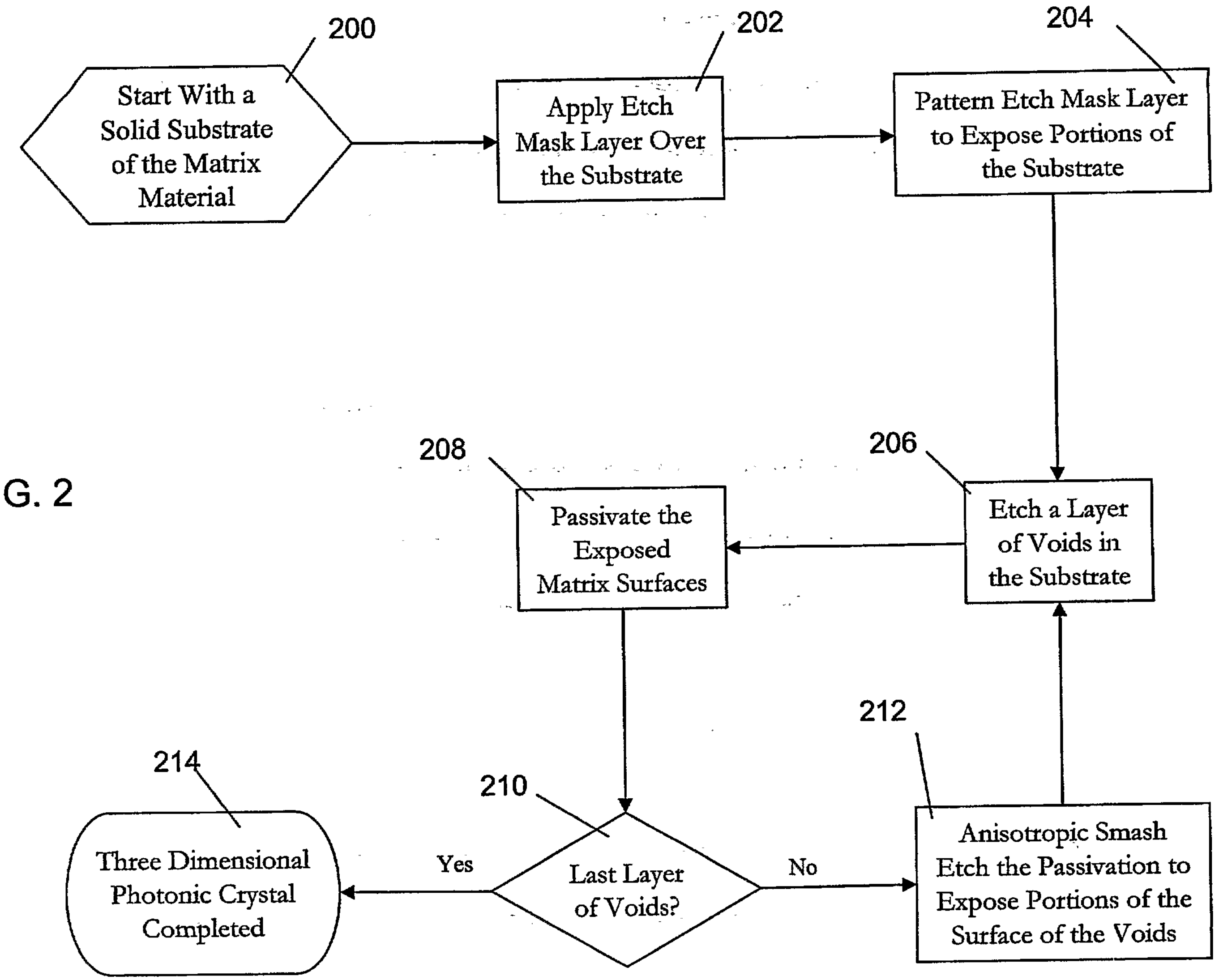

200
Start With a Solid Substrate of the Matrix Material
202
Apply Etch Mask Layer Over the Substrate
204
Pattern Etch Mask Layer to Expose Portions of the Substrate
206
Etch a Layer of Voids in the Substrate
208
Passivate the Exposed Matrix Surfaces
210
Last Layer of Voids?
Yes
No
212
Anisotropic Smash Etch the Passivation to Expose Portions of the Surface of the Voids
214
Three Dimensional Photonic Crystal Completed

FIG. 2

FIG. 3A

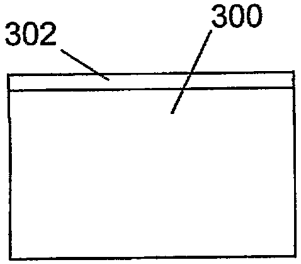


FIG. 3B

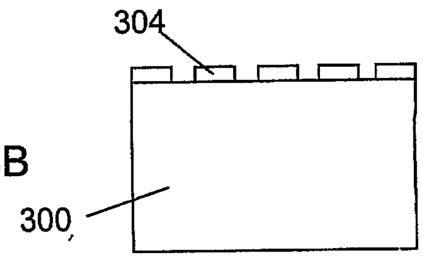


FIG. 3C

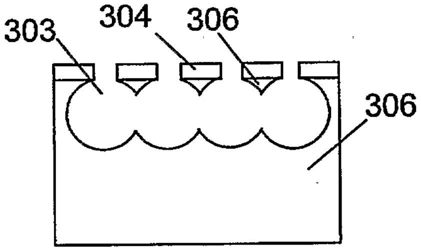


FIG. 3D

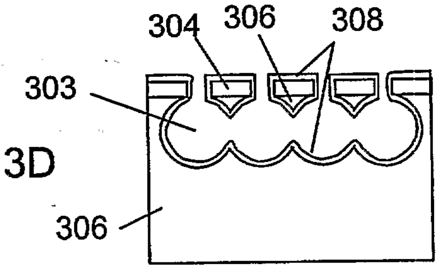


FIG. 3E

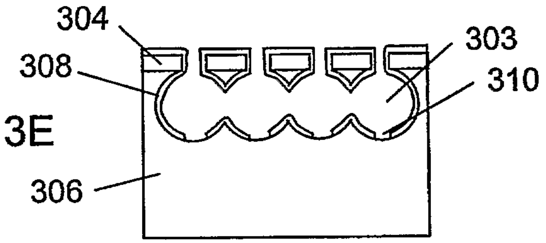


FIG. 3F

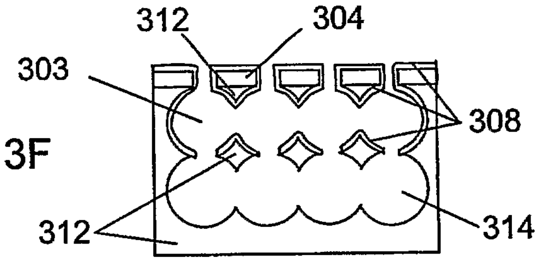


FIG. 3G

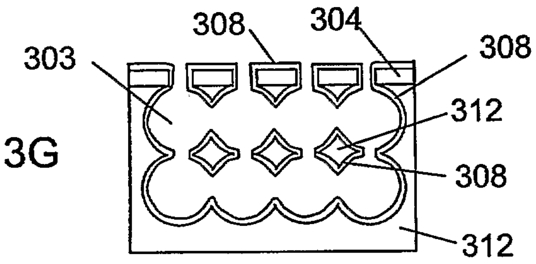


FIG. 3H

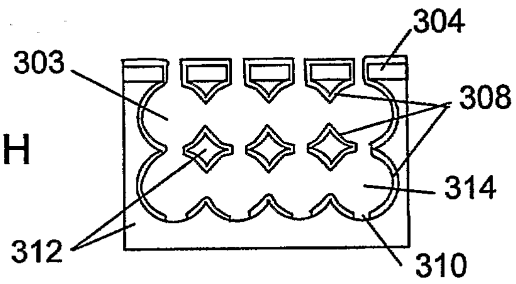
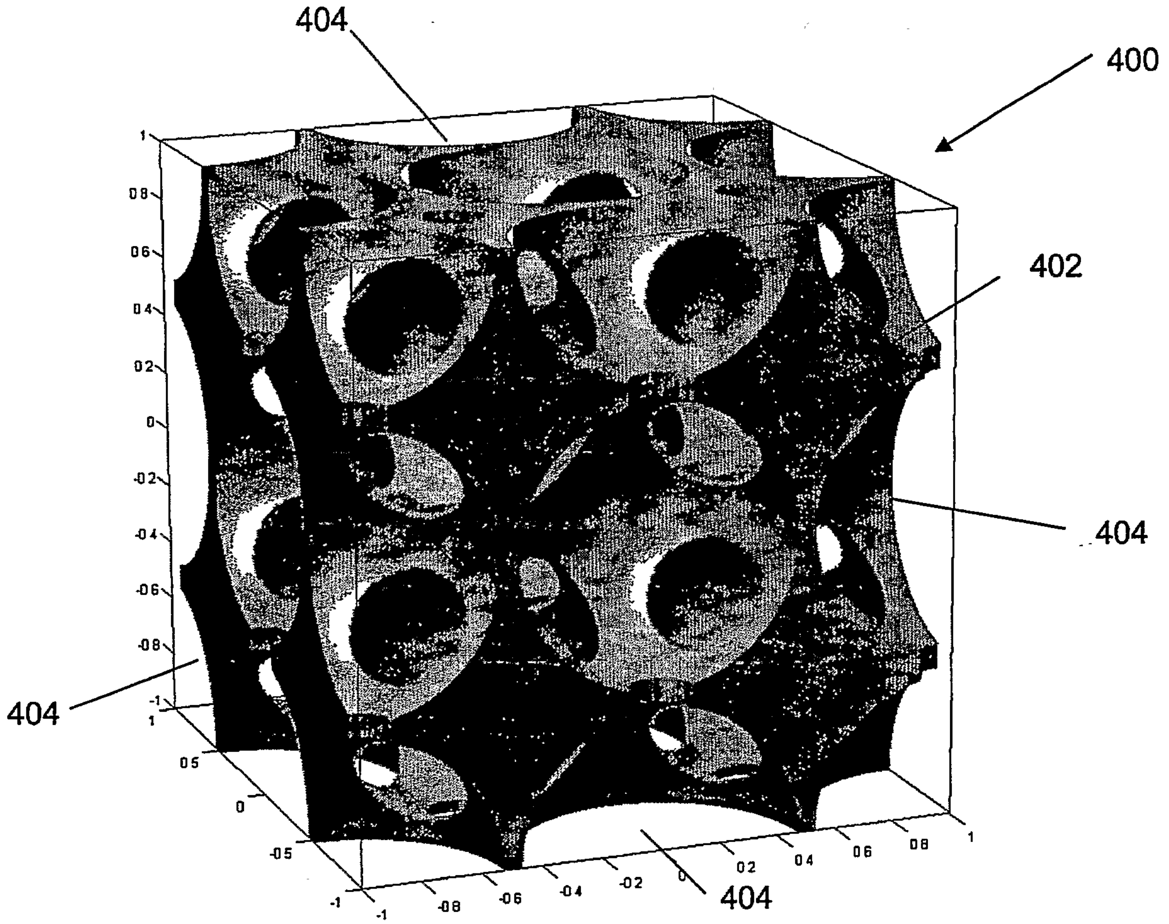


FIG. 4


400
402
404
404
404
404
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1
0.5
0
-0.5
-1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

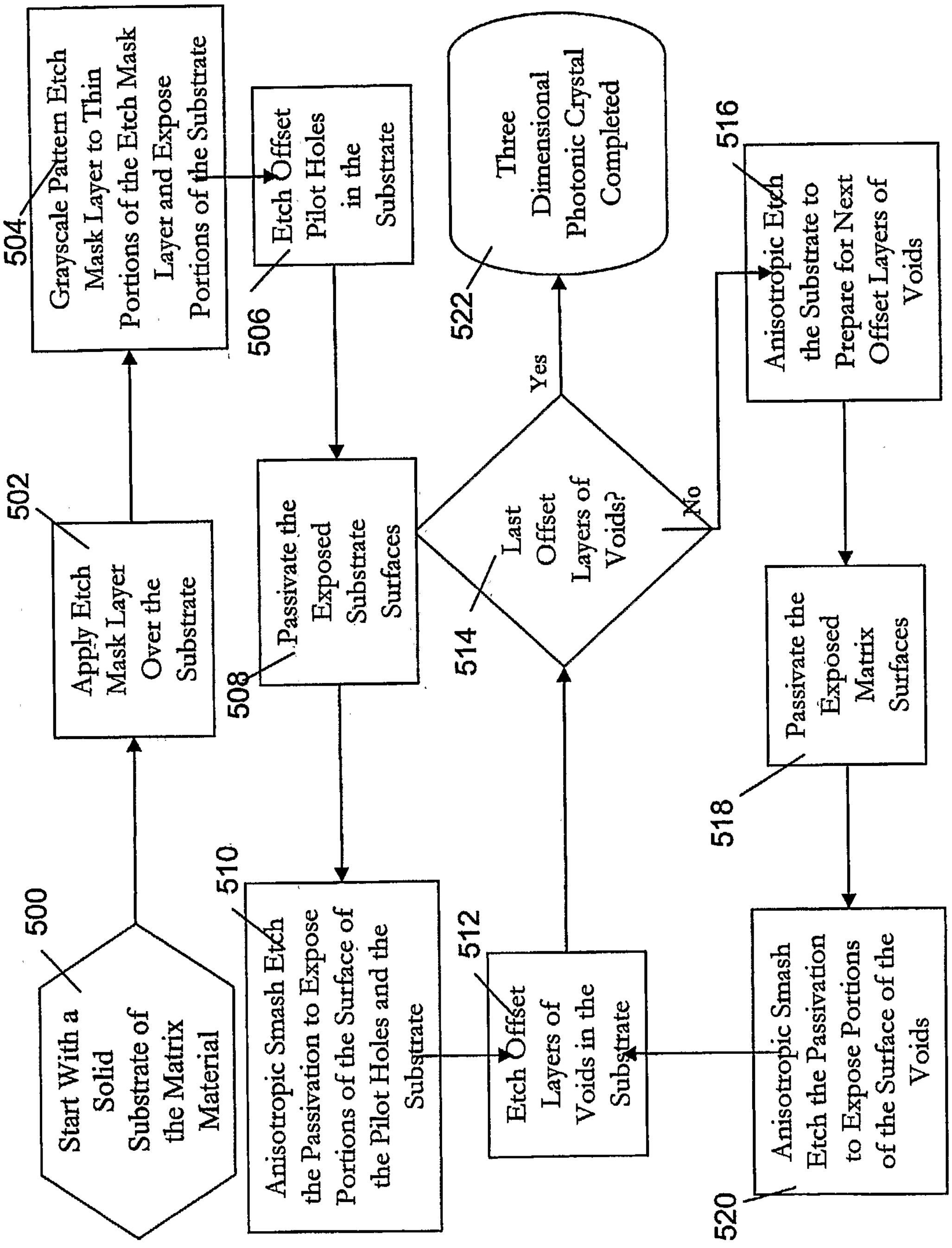

500
Start With a Solid Substrate of the Matrix Material
502
Apply Etch Mask Layer Over the Substrate
504
Grayscale Pattern Etch Mask Layer to Thin Portions of the Etch Mask Layer and Expose Portions of the Substrate
506
Etch Offset Pilot Holes in the Substrate
508
Passivate the Exposed Substrate Surfaces
510
Anisotropic Smash Etch the Passivation to Expose Portions of the Surface of the Pilot Holes and the Substrate
512
Etch Offset Layers of Voids in the Substrate
514
Last Offset Layers of Voids?
Yes
No
522
Three Dimensional Photonic Crystal Completed
516
Anisotropic Etch the Substrate to Prepare for Next Offset Layers of Voids
518
Passivate the Exposed Matrix Surfaces
520
Anisotropic Smash Etch the Passivation to Expose Portions of the Surface of the Voids

FIG. 5

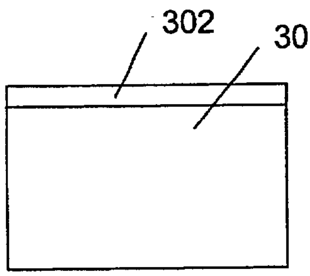


FIG. 6A

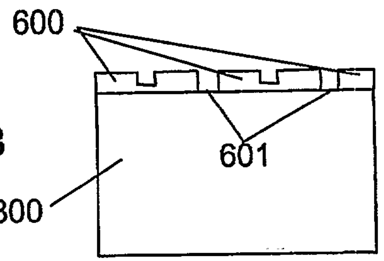


FIG. 6B

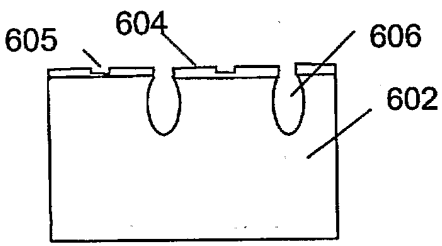


FIG 6C

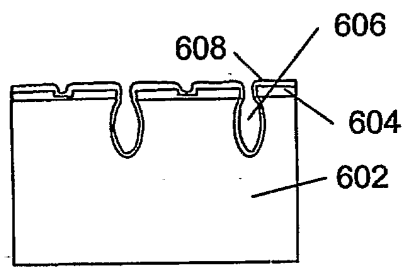


FIG. 6D

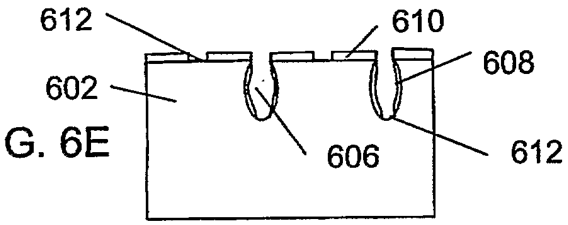


FIG. 6E

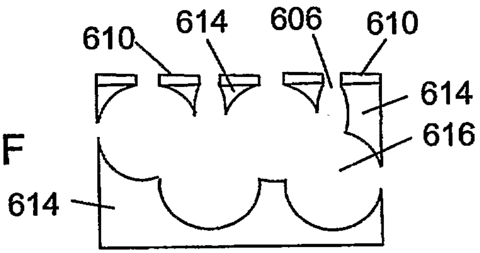


FIG. 6F

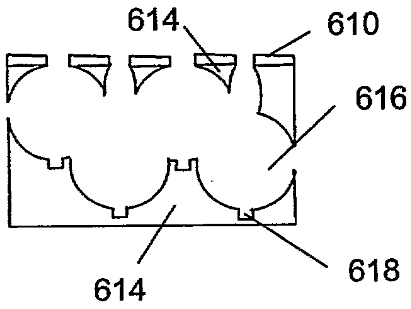


FIG. 6G

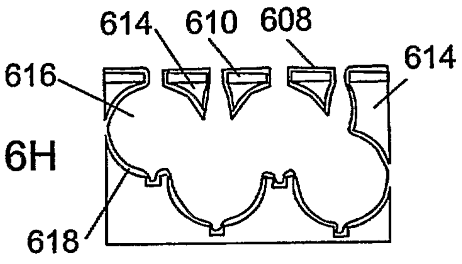


FIG. 6H

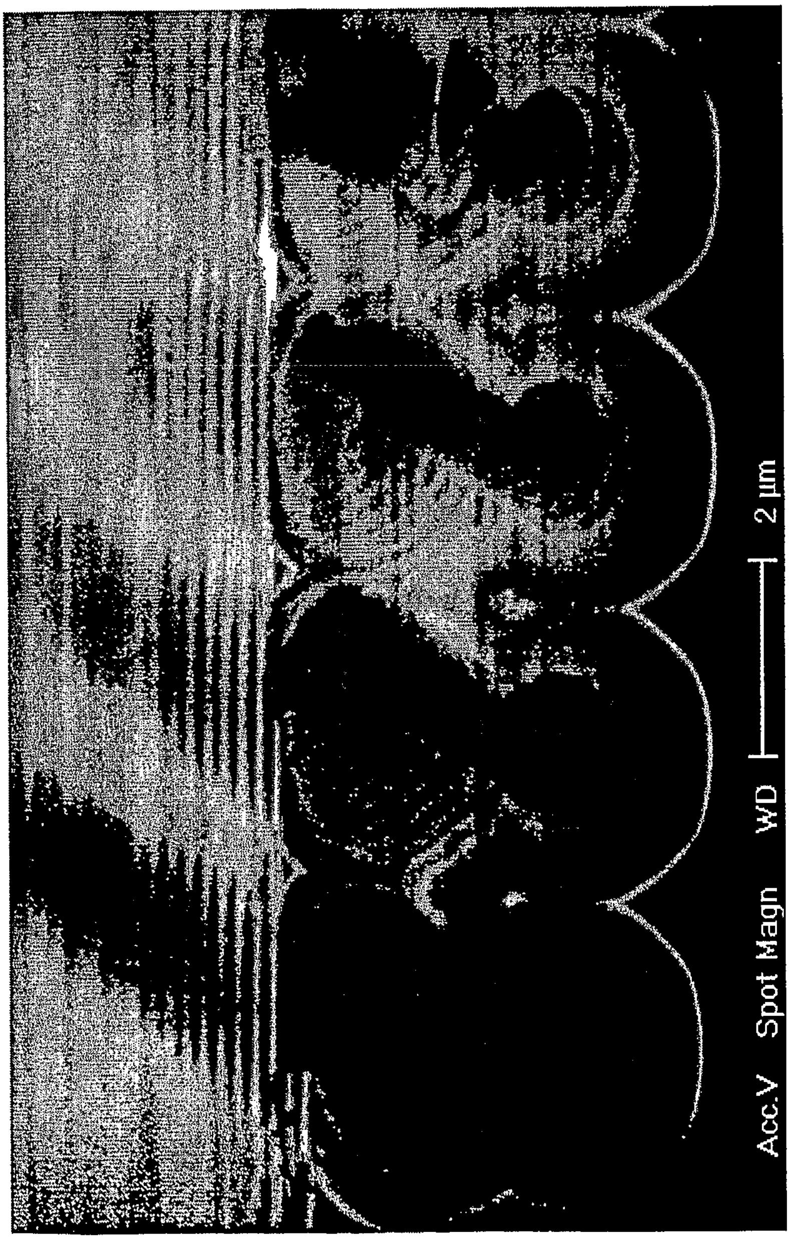


FIG. 7