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Title: A CONTROLLED CLEAVAGE PROCESS AND RESULTING DEVICE

Enclosed are:

☒ 43 pages of the specification (including description and claims).

☒ 14 sheet(s) of drawing(s).

☒ Abstract

☐ A verified statement to establish small entity status under 37 CFR 1.9 and 37 CFR 1.27.

☐ The invention was made by or under a contract with the following agency of the United States Government: _____

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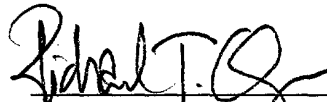
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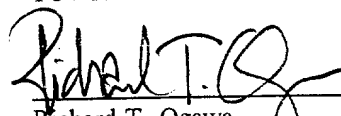
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PROVISIONAL PATENT APPLICATION

**A CONTROLLED CLEAVAGE PROCESS AND RESULTING
DEVICE**

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A CONTROLLED CLEAVAGE PROCESS AND RESULTING DEVICE

BACKGROUND OF THE INVENTION

The present invention relates to the manufacture of substrates. More particularly, the invention provides a technique including a method and device for cleaving a substrate in the fabrication of a silicon-on-insulator substrate for semiconductor integrated circuits, for example. But it will be recognized that the invention has a wider range of applicability; it can also be applied to other substrates for multi-layered integrated circuit devices, three-dimensional packaging of integrated semiconductor devices, photonic devices, piezoelectronic devices, microelectromechanical systems ("MEMS"), sensors, actuators, solar cells, flat panel displays (e.g., LCD, AMLCD), biological and biomedical devices, and the like.

Craftsmen or more properly crafts-people have been building useful articles, tools, or devices using less useful materials for numerous years. In some cases, articles are assembled by way of smaller elements or building blocks. Alternatively, less useful articles are separated into smaller pieces to improve their utility. A common example of these articles to be separated include substrate structures such as a glass plate, a diamond, a semiconductor substrate, and others.

These substrate structures are often cleaved or separated using a variety of techniques. In some cases, the substrates can be cleaved using a saw operation. The saw operation generally relies upon a rotating blade or tool, which cuts through the substrate material to separate the substrate material into two pieces. This technique, however, is often extremely "rough" and cannot generally be used for providing precision separations in the substrate for the manufacture of fine tools and assemblies. Additionally, the saw operation often has difficulty separating or cutting extremely hard and/or brittle materials such as diamond or glass.

Accordingly, techniques have been developed to separate these hard and/or brittle materials using cleaving approaches. In diamond cutting, for example, an intense directional thermal/mechanical impulse is directed preferentially

along a crystallographic plane of a diamond material. This thermal/mechanical impulse generally causes a cleave front to propagate along major crystallographic planes, where cleaving occurs when an energy level from the thermal/mechanical impulse exceeds the fracture energy level along the chosen crystallographic plane.

5 In glass cutting, a scribe line using a tool is often impressed in a preferred direction on the glass material, which is generally amorphous in character. The scribe line causes a higher stress area surrounding the amorphous glass material. Mechanical force is placed on each side of the scribe line, which increases stress along the scribe line until the glass material fractures, preferably
10 along the scribe line. This fracture completes the cleaving process of the glass, which can be used in a variety of applications including households.

Although the techniques described above are satisfactory, for the most part, as applied to cutting diamonds or household glass, they have severe limitations in the fabrication of small complex structures or precision workpieces. For
15 instance, the above techniques are often "rough" and cannot be used with great precision in fabrication of small and delicate machine tools, electronic devices, or the like. Additionally, the above techniques may be useful for separating one large plane of glass from another, but are often ineffective for splitting off, shaving, or stripping a thin film of material from a larger substrate. Furthermore, the above
20 techniques may often cause more than one cleave front, which join along slightly different planes, which is highly undesirable for precision cutting applications.

From the above, it is seen that a technique for separating a thin film of material from a substrate which is cost effective and efficient is often desirable.

25 SUMMARY OF THE INVENTION

According to the present invention, an improved technique for removing a thin film of material from a substrate using a controlled cleaving action is provided. This technique allows an initiation of a cleaving process on a substrate using a single or multiple cleave region(s) through the use of controlled energy
30 (e.g., spatial distribution) and selected conditions to allow an initiation of a cleave front(s) and to allow it to propagate through the substrate to remove a thin film of material from the substrate.

In a specific embodiment, the present invention provides a process for

forming a film of material from a donor substrate using a controlled cleaving process. The process includes a step of introducing energetic particles (e.g., charged or neutral molecules, atoms, or electrons having sufficient kinetic energy) through a surface of a donor substrate to a selected depth underneath the surface, where the particles are at a relatively high concentration to define a thickness of donor substrate material (e.g., thin film of detachable material) above the selected depth. To cleave the donor substrate material, the method provides energy to a selected region of the donor substrate to initiate a controlled cleaving action in the donor substrate, whereupon the cleaving action is made using a propagating cleave front(s) to free the donor material from a remaining portion of the donor substrate.

In an alternative embodiment, the present invention provides a process for forming a silicon-on-insulator substrate using a controlled cleaving technique. The present process includes steps of providing a donor substrate and introducing particles (e.g., charged or neutral molecules, atoms, or electrons having sufficient kinetic energy) through a surface of the donor substrate to a selected depth underneath the surface. The particles are at a concentration at the selected depth to define a thickness of substrate material (e.g., thin film of material) to be removed above the selected depth. The multi-layered silicon-on-insulator structure is formed by joining the donor substrate to a target substrate such that the surface of the donor substrate faces a face of the target substrate. A controlled cleaving action to free the thin film of material occurs by providing energy to a selected region of the combined substrate structure to initiate the controlled cleaving action at the selected depth in the substrate, whereupon the cleaving action is made using a propagating cleave front to free a portion of the material to be removed from the substrate. In some embodiments, the step of providing energy sustains the controlled cleaving action to remove the material from the substrate to provide the thin film of material. Alternatively, the method uses an additional step(s) of providing additional energy to the substrate to sustain the controlled cleaving action to remove the material from the substrate to provide the film of material. The resulting substrate is the silicon-on-insulator structure.

In most of the embodiments, a cleave is initiated by subjecting the material with sufficient energy to fracture the material in one region, causing a cleave front, without uncontrolled shattering or cracking. The cleave front

formation energy (E_c) must often be made lower than the bulk material fracture energy (E_{mat}) at each region to avoid shattering or cracking the material. The directional energy impulse vector in diamond cutting or the scribe line in glass cutting are, for example, the means in which the cleave energy is reduced to allow the controlled creation and propagation of a cleave front. The cleave front is in itself a higher stress region and once created, its propagation requires a lower energy to further cleave the material from this initial region of fracture. The energy required to propagate the cleave front is called the cleave front propagation energy (E_p). The relationship can be expressed as:

$$E_c = E_p + [\text{cleave front stress energy}]$$

A controlled cleaving process is realized by reducing E_p along a favored direction(s) above all others and limiting the available energy to be below the E_p of other undesired directions. In any cleave process, a better cleave surface finish occurs when the cleave process occurs through only one expanding cleave front, although multiple cleave fronts do work.

Numerous benefits are achieved over pre-existing techniques using the present invention. In particular, the present invention uses controlled energy and selected conditions to preferentially cleave a thin film of material from a donor substrate which includes multi-material sandwiched films. This cleaving process selectively removes the thin film of material from the substrate while preventing a possibility of damage to the film or a remaining portion of the substrate. Accordingly, the remaining substrate portion can be re-used repeatedly for other applications.

Additionally, the present invention uses a relatively low temperature during the controlled cleaving process of the thin film to reduce temperature excursions of the separated film, donor substrate, or multi-material films according to other embodiments. This lower temperature approach allows for more material and process latitude such as, for example, cleaving and bonding of materials having substantially different thermal expansion coefficients. In other embodiments, the present invention limits energy or stress in the substrate to a value below a cleave initiation energy, which generally removes a possibility of creating random cleave

initiation sites or fronts. This reduces cleave damage (e.g., pits, crystalline defects, breakage, cracks, steps, voids, excessive roughness) often caused in pre-existing techniques. Moreover, the present invention reduces damage caused by higher than necessary stress or pressure effects and nucleation sites caused by the energetic particles as compared to pre-existing techniques.

The present invention achieves these benefits and others in the context of known process technology. However, a further understanding of the nature and advantages of the present invention may be realized by reference to the latter portions of the specification and attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1-11 are simplified diagrams illustrating a controlled cleaving technique according to an embodiment of the present invention;

Figs. 12-20 are simplified diagrams of implanting particles in patterns according to alternative aspects of the present invention; and

Figs. 20-28 are simplified cross-sectional view diagrams illustrating a method of forming a silicon-on-insulator substrate according to the present invention.

DESCRIPTION OF THE SPECIFIC EMBODIMENT

The present invention provides a technique for removing a thin film of material from a substrate while preventing a possibility of damage to the thin material film and/or a remaining portion of the substrate. The thin film of material is attached to or can be attached to a target substrate to form, for example, a silicon-on-insulator wafer. The thin film of material can also be used for a variety of other applications. The invention will be better understood by reference to the Figs. and the descriptions below.

1. Controlled Cleaving Techniques

Fig. 1 is a simplified cross-sectional view diagram of a substrate according to the present invention. The diagram is merely an illustration and should not limit the scope of the claims herein. As merely an example, substrate is a silicon wafer which includes a material region 12 to be removed, which is a

thin relatively uniform film derived from the substrate material. The silicon wafer 10 includes a top surface 14, a bottom surface 16, and a thickness 18. Substrate 10 also has a first side (side 1) and a second side (side 2) (which are also referenced below in the Figs.). Material region 12 also includes a thickness 20, within the

5 thickness 18 of the silicon wafer. The present invention provides a novel technique for removing the material region 12 using the following sequence of steps.

Selected energetic particles implant 22 through the top surface 14 of the silicon wafer to a selected depth 24, which defines the thickness 20 of the material region 12, termed the thin film of material. A variety of techniques can be

10 used to implant the energetic particles into the silicon wafer. These techniques include ion implantation using, for example, beam line ion implantation equipment manufactured from companies such as Applied Materials, Eaton Corporation, Varian, and others. Alternatively, implantation occurs using a plasma immersion ion implantation ("PIII") technique. Examples of plasma immersion implantation

15 techniques are described in "Recent Applications of Plasma Immersion Ion Implantation," Paul K. Chu, Chung Chan, and Nathan W. Cheung, SEMICONDUCTOR INTERNATIONAL, pp. 165-172, June 1996, and "Plasma Immersion Ion Implantation - A Fledgling Technique for Semiconductor Processing," P.K. Chu, S. Qin, C. Chan, N.W. Cheung, and L.A. Larson,

20 Volume R17, Nos. 6-7, (Nov. 30, 1996), which are both hereby incorporated by reference for all purposes. Of course, techniques used depend upon the application.

Depending upon the application, smaller mass particles are generally selected to reduce a possibility of damage to the material region 12. That is, smaller mass particles easily travel through the substrate material to the selected

25 depth without substantially damaging the material region that the particles traverse through. For example, the smaller mass particles (or energetic particles) can be almost any charged (e.g., positive or negative) and/or neutral atoms or molecules, or electrons, or the like. In a specific embodiment, the particles can be neutral and/or charged particles including ions such as ions of hydrogen and its isotopes, rare gas ions such as helium and its isotopes, and neon. The particles can also be

30 derived from compounds such as gases, e.g., hydrogen gas, water vapor, methane, and hydrogen compounds, and other light atomic mass particles. Alternatively, the particles can be any combination of the above particles, and/or ions and/or

ions and/or molecular species and/or atomic species. The particles generally have sufficient kinetic energy to penetrate through the surface to the selected depth underneath the surface.

Using hydrogen as the implanted species into the silicon wafer as an example, the implantation process is performed using a specific set of conditions. Implantation dose ranges from about 10^{15} to about 10^{18} atoms/cm², and preferably the dose is greater than about 10^{16} atoms/cm². Implantation energy ranges from about 1 KeV to about 1 MeV, and is generally about 50 KeV. Implantation temperature ranges from about -200 to about 600°C, and is preferably less than about 400°C to prevent a possibility of a substantial quantity of hydrogen ions from diffusing out of the implanted silicon wafer and annealing the implanted damage and stress. The hydrogen ions can be selectively introduced into the silicon wafer to the selected depth at an accuracy of about +/- 0.03 to +/- 0.05 microns. Of course, the type of ion used and process conditions depend upon the application.

Effectively, the implanted particles add stress or reduce fracture energy along a plane parallel to the top surface of the substrate at the selected depth. The energies depend, in part, upon the implantation species and conditions. These particles reduce a fracture energy level of the substrate at the selected depth. This allows for a controlled cleave along the implanted plane at the selected depth. Implantation can occur under conditions such that the energy state of substrate at all internal locations is insufficient to initiate a non-reversible fracture (i.e., separation or cleaving) in the substrate material. It should be noted, however, that implantation does generally cause a certain amount of defects (e.g., micro-defects) in the substrate that can be repaired by subsequent heat treatment, e.g., thermal annealing or rapid thermal annealing.

Fig. 2 is a simplified energy diagram 200 along a cross-section of the implanted substrate 10 according to the present invention. The diagram is merely an illustration and should not limit the scope of the claims herein. The simplified diagram includes a vertical axis 201 that represents an energy level (E) (or additional energy) to cause a cleave in the substrate. A horizontal axis 203 represents a depth or distance from the bottom of the wafer to the top of the wafer. After implanting particles into the wafer, the substrate has an average cleave energy represented as E 205, which is the amount of energy needed to cleave the wafer

along various cross-sectional regions along the wafer depth. The cleave energy (E_c) is equal to the bulk material fracture energy (E_{mat}) in non-implanted regions. At the selected depth 20, energy (E_{cz}) 207 is lower since the implanted particles essentially break or weaken bonds in the crystalline structure (or increase stress caused by a presence of particles also contributing to lower energy (E_{cz}) 207 of the substrate) to lower the amount of energy needed to cleave the substrate at the selected depth. The present invention takes advantage of the lower energy (or increased stress) at the selected depth to cleave the thin film in a controlled manner.

Substrates, however, are not generally free from defects or "weak" regions across the possible cleave front or selected depth z_0 after the implantation process. In these cases, the cleave generally cannot be controlled, since they are subject to random variations such as bulk material non-uniformities, built-in stresses, defects, and the like. Fig. 3 is a simplified energy diagram 300 across a cleave front for the implanted substrate 10 having these defects. The diagram 300 is merely an illustration and should not limit the scope of the claims herein. The diagram has a vertical axis 301 which represents additional energy (E) and a horizontal axis 303 which represents a distance from side 1 to side 2 of the substrate, that is, the horizontal axis represents regions along the cleave front of the substrate. As shown, the cleave front has two regions 305 and 307 represented as region 1 and region 2, respectively, which have cleave energies less than the average cleave energy (E_{cz}) 207 (possibly due to a higher concentration of defects or the like). Accordingly, it is highly likely that the cleave process begins at one or both of the above regions, since each region has a lower cleave energy than surrounding regions.

An example of a cleave process for the substrate illustrated by the above Fig. is described as follows with reference to Fig. 4. Fig. 4 is a simplified top-view diagram 400 of multiple cleave fronts 401, 403 propagating through the implanted substrate. The cleave fronts originate at "weaker" regions in the cleave plane, which specifically includes regions 1 and 2. The cleave fronts originate and propagate randomly as shown by the arrows. A limitation with the use of random propagation among multiple cleave fronts is the possibility of having different cleave fronts join along slightly different planes or the possibility of forming cracks, which is described in more detail below.

Fig. 5 is a simplified cross-sectional view 500 of a film cleaved from a wafer having multiple cleave fronts at, for example, regions 1 305 and 2 307. This diagram is merely an illustration and should not limit the scope of the claims herein. As shown, the cleave from region 1 joined with the cleave from region 2 at region 3 309, which is defined along slightly different planes, may initiate a secondary cleave or crack 311 along the film. Depending upon the magnitude of the difference 313, the film may not be of sufficient quality for use in manufacture of substrates for integrated circuits or other applications. A substrate having crack 311 generally cannot be used for processing. Accordingly, it is generally undesirable to cleave a wafer using multiple fronts in a random manner. An example of a technique which may form multiple cleave fronts in a random manner is described in U.S. Patent No. 5,374,564, which is in the name of Michel Bruel ("Bruel"), and assigned to Commissariat A l'Energie Atomique in France. Bruel generally describes a technique for cleaving an implanted wafer by global thermal treatment (i.e., thermally treating the entire plane of the implant) using thermally activated diffusion. Global thermal treatment of the substrate generally causes an initiation of multiple cleave fronts which propagate independently. In general, Bruel discloses a technique for an "uncontrollable" cleaving action by way of initiating and maintaining a cleaving action by a global thermal source, which may produce undesirable results. These undesirable results include potential problems such as an imperfect joining of cleave fronts, an excessively rough surface finish on the surface of the cleaved material since the energy level for maintaining the cleave exceeds the amount required, and many others. The present invention overcomes the formation of random cleave fronts by a controlled distribution or selective positioning of energy on the implanted substrate.

Fig. 6 is a simplified cross-sectional view of an implanted substrate 10 using selective positioning of cleave energy according to the present invention. This diagram is merely an illustration, and should not limit the scope of the claims herein. The implanted wafer undergoes a step of selective energy placement or positioning or targeting which provides a controlled cleaving action of the material region 12 at the selected depth. The impulse or impulses are provided using energy sources. Examples of sources include, among others, a chemical source, a mechanical source, an electrical source, and a thermal sink or source. The

chemical source can include a variety such as particles, fluids, gases, or liquids. These sources can also include chemical reaction to increase stress in the material region. The chemical source is introduced as flood, time-varying, spatially varying, or continuous. In other embodiments, a mechanical source is derived from

5 rotational, translational, compressional, expansional, or ultrasonic energies. The mechanical source can be introduced as flood, time-varying, spatially varying, or continuous. In further embodiments, the electrical source is selected from an applied voltage or an applied electro-magnetic field, which is introduced as flood, time-varying, spatially varying, or continuous. In still further embodiments, the

10 thermal source or sink is selected from radiation, convection, or conduction. This thermal source can be selected from, among others, a photon beam, a fluid jet, a liquid jet, a gas jet, an electro/magnetic field, a gas jet, an electron beam, a thermo-electric heating, a furnace, and the like. The thermal sink can be selected from a fluid jet, a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a thermo-

15 electric cooling means, an electro/magnetic field, and others. Similar to the previous embodiments, the thermal source is applied as flood, time-varying, spatially varying, or continuous. Still further, any of the above embodiments can be combined or even separated, depending upon the application. Of course, the type of source used depends upon the application.

20 In a specific embodiment, the present invention provides a controlled-propagating cleave. The controlled-propagating cleave uses multiple successive impulses to initiate and perhaps propagate a cleaving process 700, as illustrated by Fig. 7. This diagram is merely an illustration, and should not limit the scope of the claims herein. As shown, the impulse is directed at an edge of the substrate, which

25 propagates a cleave front toward the center of the substrate to remove the material layer from the substrate. In this embodiment, a source applies multiple pulses (i.e., pulse 1, 2, and 3) successively to the substrate. Pulse 1 701 is directed to an edge 703 of the substrate to initiate the cleave action. Pulse 2 705 is also directed at the edge 707 on one side of pulse 1 to expand the cleave front. Pulse 3 709 is directed

30 to an opposite edge 711 of pulse 1 along the expanding cleave front to further remove the material layer from the substrate. The combination of these impulses or pulses provides a controlled cleaving action 713 of the material layer from the substrate.

Fig. 8 is a simplified illustration of selected energies 800 from the pulses in the preceding embodiment for the controlled-propagating cleave. This diagram is merely an illustration, and should not limit the scope of the claims herein. As shown, the pulse 1 has an energy level which exceeds average cleaving energy (E), which is the necessary energy for initiating the cleaving action. Pulses 2 and 3 are made using lower energy levels along the cleave front to maintain or sustain the cleaving action. In a specific embodiment, the pulse is a laser pulse where an impinging beam heats a selected region of the substrate through a pulse and a thermal pulse gradient causes supplemental stresses which together exceed cleave formation or propagation energies, which create a single cleave front. In preferred embodiments, the impinging beam heats and causes a thermal pulse gradient simultaneously, which exceed cleave energy formation or propagation energies. More preferably, the impinging beam cools and causes a thermal pulse gradient simultaneously, which exceed cleave energy formation or propagation energies.

Optionally, a built-in energy state of the substrate or stress can be globally raised toward the energy level necessary to initiate the cleaving action, but not enough to initiate the cleaving action before directing the multiple successive impulses to the substrate according to the present invention. The global energy state of the substrate can be raised or lowered using a variety of sources such as chemical, mechanical, thermal (sink or source), or electrical, alone or in combination. The chemical source can include a variety such as particles, fluids, gases, or liquids. These sources can also include chemical reaction to increase stress in the material region. The chemical source is introduced as flood, time-varying, spatially varying, or continuous. In other embodiments, a mechanical source is derived from rotational, translational, compressional, expansional, or ultrasonic energies. The mechanical source can be introduced as flood, time-varying, spatially varying, or continuous. In further embodiments, the electrical source is selected from an applied voltage or an applied electro-magnetic field, which is introduced as flood, time-varying, spatially varying, or continuous. In still further embodiments, the thermal source or sink is selected from radiation, convection, or conduction. This thermal source can be selected from, among others, a photon beam, a fluid jet, a liquid jet, a gas jet, an electro/magnetic field, a

gas jet, an electron beam, a thermo-electric heating, and a furnace. The thermal sink can be selected from a fluid jet, a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a thermo-electric cooling means, an electro/magnetic field, and others. Similar to the previous embodiments, the thermal source is applied as
 5 flood, time-varying, spatially varying, or continuous. Still further, any of the above embodiments can be combined or even separated, depending upon the application. Of course, the type of source used also depends upon the application. As noted, the global source increases a level of energy or stress in the material region without initiating a cleaving action in the material region before providing energy to initiate
 10 the controlled cleaving action.

In a specific embodiment, an energy source elevates an energy level of the substrate cleave plane above its cleave front propagation energy but is insufficient to cause self-initiation of a cleave front. In particular, a thermal energy source or sink in the form of heat or lack of heat (e.g., cooling source) can be
 15 applied globally to the substrate to increase the energy state or stress level of the substrate without initiating a cleave front. Alternatively, the energy source can be electrical, chemical, or mechanical. A directed energy source provides an application of energy to a selected region of the substrate material to initiate a cleave front which self-propagates through the implanted region of the substrate
 20 until the thin film of material is removed. A variety of techniques can be used to initiate the cleave action. These techniques are described by way of the Figs. below.

Fig. 9 is a simplified illustration of an energy state 900 for a controlled cleaving action using a single controlled source according to an aspect of
 25 the present invention. This diagram is merely an illustration, and should not limit the scope of the claims herein. In this embodiment, the energy level or state of the substrate is raised using a global energy source above the cleave front propagation energy state, but is lower than the energy state necessary to initiate the cleave front. To initiate the cleave front, an energy source such as a laser directs a beam in the
 30 form of a pulse at an edge of the substrate to initiate the cleaving action. Alternatively, the energy source can be a cooling fluid (e.g., liquid, gas) that directs a cooling medium in the form of a pulse at an edge of the substrate to initiate the cleaving action. The global energy source maintains the cleaving action which

generally requires a lower energy level than the initiation energy.

An alternative aspect of the invention is illustrated by Figs. 10 and 11. Fig. 10 is a simplified illustration of an implanted substrate 1000 undergoing rotational forces 1001, 1003. This diagram is merely an illustration, and should not limit the scope of the claims herein. As shown, the substrate includes a top surface 1005, a bottom surface 1007, and an implanted region 1009 at a selected depth. An energy source increases a global energy level of the substrate using a light beam or heat source to a level above the cleave front propagation energy state, but lower than the energy state necessary to initiate the cleave front. The substrate undergoes a rotational force turning clockwise 1001 on top surface and a rotational force turning counter-clockwise 1003 on the bottom surface which creates stress at the implanted region 1009 to initiate a cleave front. Alternatively, the top surface undergoes a counter-clockwise rotational force and the bottom surface undergoes a clockwise rotational force. Of course, the direction of the force generally does not matter in this embodiment.

Fig. 11 is a simplified diagram of an energy state 1100 for the controlled cleaving action using the rotational force according to the present invention. This diagram is merely an illustration, and should not limit the scope of the claims herein. As previously noted, the energy level or state of the substrate is raised using a global energy source (e.g., thermal, beam) above the cleave front propagation energy state, but is lower than the energy state necessary to initiate the cleave front. To initiate the cleave front, a mechanical energy means such as rotational force applied to the implanted region initiates the cleave front. In particular, rotational force applied to the implanted region of the substrates creates zero stress at the center of the substrate and greatest at the periphery, essentially being proportional to the radius. In this example, the central initiating pulse causes a radially expanding cleave front to cleave the substrate.

The removed material region provides a thin film of silicon material for processing. The silicon material possesses limited surface roughness and desired planarity characteristics for use in a silicon-on-insulator substrate. In certain embodiments, the surface roughness of the detached film has features that are less than about 60 nm, or less than about 40 nm, or less than about 20 nm. Accordingly, the present invention provides thin silicon films which can be

smoother and more uniform than pre-existing techniques.

In a preferred embodiment, the present invention is practiced at temperatures that are lower than those used by pre-existing techniques. In particular, the present invention does not require increasing the entire substrate temperature to initiate and sustain the cleaving action as pre-existing techniques. In some embodiments for silicon wafers and hydrogen implants, substrate temperature does not exceed about 400°C during the cleaving process. Alternatively, substrate temperature does not exceed about 350°C during the cleaving process. Alternatively, substrate temperature is kept substantially below implanting temperatures via a thermal sink, e.g., cooling fluid, cryogenic fluid. Accordingly, the present invention reduces a possibility of unnecessary damage from an excessive release of energy from random cleave fronts, which generally improves surface quality of a detached film(s) and/or the substrate(s). Accordingly, the present invention provides resulting films on substrates at higher overall yields and quality.

The above embodiments are described in terms of cleaving a thin film of material from a substrate. The substrate, however, can be disposed on a workpiece such as a stiffener or the like before the controlled cleaving process. The workpiece joins to a top surface or implanted surface of the substrate to provide structural support to the thin film of material during controlled cleaving processes. The workpiece can be joined to the substrate using a variety of bonding or joining techniques, e.g., electro-statics, adhesives, interatomic. Some of these bonding techniques are described herein. The workpiece can be made of a dielectric material (e.g., quartz, glass, sapphire, silicon nitride, silicon dioxide), a conductive material (silicon, silicon carbide, polysilicon, group III/V materials, metal), and plastics (e.g., polyimide-based materials). Of course, the type of workpiece used will depend upon the application.

Alternatively, the substrate having the film to be detached can be temporarily disposed on a transfer substrate such as a stiffener or the like before the controlled cleaving process. The transfer substrate joins to a top surface or implanted surface of the substrate having the film to provide structural support to the thin film of material during controlled cleaving processes. The transfer substrate can be temporarily joined to the substrate having the film using a variety of bonding or joining techniques, e.g., electro-statics, adhesives, interatomic. Some

of these bonding techniques are described herein. The transfer substrate can be made of a dielectric material (e.g., quartz, glass, sapphire, silicon nitride, silicon dioxide), a conductive material (silicon, silicon carbide, polysilicon, group III/V materials, metal), and plastics (e.g., polyimide-based materials). Of course, the type of transfer substrate used will depend upon the application. Additionally, the transfer substrate can be used to remove the thin film of material from the cleaved substrate after the controlled cleaving process.

2. Patterned Implanting Techniques

Although the embodiments in this specification are in terms of general implanting techniques, controlled cleaving can be enhanced by way of patterned implanting techniques according to the present invention. Patterned implanting techniques are used to selectively introduce impurities into the substrate using a desired or selected pattern, which enhances the control for the cleaving process. Figs. 12-20 illustrate a few examples of implanting techniques according to this embodiment of the present invention. These Figs. are merely illustrations and should not limit the scope of the claims herein. One of ordinary skill in the art would recognize other variations, alternatives, and modifications.

Fig. 12 is a simplified cross-sectional view diagram 1200 of an implanting step using a patterned mask 1201 according to the present invention. The patterned mask is merely an illustration and should not limit the scope of the claims herein. Patterned mask 1201 is a shadow mask, but also can be others. The patterned implanting step 1203 provides a patterned distribution 1205 of particles at a selected depth (z_0). For instance, the patterned mask can be applied directly to the substrate using photolithographic techniques. An example of numerous photolithographic techniques are described in "Semiconductor Lithography, Principles, Practices, and Materials," Wayne M. Moreau, Plenum Press (1988), which is hereby incorporated by reference for all purposes.

Optionally, the present method uses a blanket implanting step 1300 of the substrate surface after the patterned implanting step described, as illustrated by Fig. 13. The blanket implanting step provides a uniform distribution of particles through the surface of the substrate to a selected depth (z_0). An example of a distribution of particles in the substrate after a two-step implanting process using

patterned and blanket implanting steps is illustrated by the simplified diagram of Fig. 14. As shown, the diagram 1400 has a vertical axis representing particle concentration at the selected depth (z_0), and has a horizontal axis representing distance from side 1 of the substrate to side 2 of the substrate. Using the two-step process described above, which includes a blanket implanting step and a patterned implanting step, concentration distribution 1401 through the cleave plane from side 1 to side 2 of the substrate varies periodically and spatially from C_1 to C_2 . Depending upon the technique for cleaving the substrate, various patterns can be used, and are illustrated by Figs. 15-18.

Fig. 15 is a simplified top-view diagram 1500 of an annular distribution of particles according to the present invention. This distribution of particles includes a lower concentration region 1505 and a higher concentration region 1501. The higher concentration region 1501 is defined in concentric annular patterns around a center region 1503 of the substrate. As shown, the annular patterns are defined symmetrically around the center of the substrate and have a plurality of annular regions which are placed next to each other in a constant spatial frequency. The annular patterns tend to enhance the controlled cleaving action according to some embodiments of the present invention.

Alternatively, the distribution of particles in the substrate can be in a linear pattern 1600, as illustrated by Fig. 16. As shown, the substrate includes particles having higher and lower concentrations in regions 1601 and 1603, respectively. The linear pattern has regions (i.e., lines) of higher concentration. The regions also have similar widths, but can include other widths. Additionally, the linear pattern has regions (i.e., lines) of lower concentration. The lower concentration regions have similar widths, but also can include other widths. Again, this pattern is likely to enhance the controlled cleaving action according to embodiments of the present invention.

Alternatively, Fig. 17 is a simplified top-view diagram 1700 of a "checker board" pattern of particles according to an alternative aspect of the present invention. The diagram 1700 illustrates a higher concentration region 1701 and a lower concentration region 1705. Higher concentration regions include vertical lines 1702 and horizontal lines 1703, which are disposed at a relatively constant spatial frequency. Of course, the use of this pattern will depend upon the particular

application.

Alternatively, Fig. 18 is a simplified top-view diagram 1800 of a "webbed" or "dart board" pattern of particles according to yet an alternative embodiment of the present invention. This pattern 1800 includes concentric annular regions 1801 of higher concentration, and other higher concentration regions 1803 (i.e., lines) which intersect the annular regions. Lower concentration regions 1805 are also shown. The annular regions have a spatial frequency that is relatively constant, but can also be others, i.e. non-constant. Again, the use of this particular embodiment will depend upon the application.

Figs. 19-20 are simplified top-view diagrams 1900, 2000 of still further particle distributions according to the present invention. These distributions of particles do not have features of constant spatial frequency. In particular, the diagram 1900 of Fig. 19 has a higher concentration region 1901 which has a higher density of particles on one side 1903 of the substrate as compared to the other side 1905 of the substrate. The higher concentration region 1903 includes a plurality of lines, which have different sized widths (but can also be similar). Additionally, lower concentration regions 1905 have a larger spatial distribution on one side 1905 of the substrate as compared to the other side 1903 of the substrate. The higher concentration regions 1901 do not generally run parallel to each other but diverge from each other as they run from one side 1903 of the substrate to the other side 1905 of the substrate. The diagram 2000 of Fig. 20 has a plurality of "wavy" higher concentration regions 2001 that run relatively parallel to each other from one side of the substrate to the other side of the substrate. As shown, the higher concentration regions 2001 are a plurality of wavy lines. These lines each have a relatively similar width, but do not have to. Lower concentration regions 2003 are defined between the higher concentration regions. Depending upon the particular cleaving technique, these patterns can be used.

Although the description above is in terms of a two-step implanting process for creating the distribution of particles in the substrate. The process can be a single step process, as well as multi-step processes using a combination of the above patterns and others. Of course, the particular sequence of implanting steps used depends upon the application.

3. Silicon-On-Insulator Process

A process for fabricating a silicon-on-insulator substrate according to the present invention may be briefly outlined as follows:

- 5 (1) Provide a donor silicon wafer (which may be coated with a dielectric material);
- (2) Introduce particles into the silicon wafer to a selected depth to define a thickness of silicon film;
- (3) Provide a target substrate material (which may be coated with a dielectric material);
- 10 (4) Bond the donor silicon wafer to the target substrate material by joining the implanted face to the target substrate material;
- (5) Increase global stress (or energy) of implanted region at selected depth without initiating a cleaving action (optional);
- (6) Provide stress (or energy) to a selected region of the bonded
15 substrates to initiate a controlled cleaving action at the selected depth;
- (7) Provide additional energy to the bonded substrates to sustain the controlled cleaving action to free the thickness of silicon film from the silicon wafer (optional);
- (8) Complete bonding of donor silicon wafer to the target substrate; and
- 20 (9) Polish a surface of the thickness of silicon film.

The above sequence of steps provides a step of initiating a controlled cleaving action using an energy applied to a selected region(s) of a multi-layered substrate structure to form a cleave front(s) according to the present invention. This
25 initiation step begins a cleaving process in a controlled manner by limiting the amount of energy applied to the substrate. Further propagation of the cleaving action can occur by providing additional energy to selected regions of the substrate to sustain the cleaving action, or using the energy from the initiation step to provide for further propagation of the cleaving action. This sequence of steps is merely an
30 example and should not limit the scope of the claims defined herein. Further details with regard to the above sequence of steps are described in below in references to the Figs.

Figs. 21-28 are simplified cross-sectional view diagrams of substrates

undergoing a fabrication process for a silicon-on-insulator wafer according to the present invention. The process begins by providing a semiconductor substrate similar to the silicon wafer 2100, as shown by Fig. 21. Substrate or donor includes a material region 2101 to be removed, which is a thin relatively uniform film
 5 derived from the substrate material. The silicon wafer includes a top surface 2103, a bottom surface 2105, and a thickness 2107. Material region also includes a thickness (z_0), within the thickness 2107 of the silicon wafer. Optionally, a dielectric layer 2102 (e.g., silicon nitride, silicon oxide, silicon oxynitride) overlies the top surface of the substrate. The present process provides a novel technique for
 10 removing the material region 2101 using the following sequence of steps for the fabrication of a silicon-on-insulator wafer.

Selected energetic particles 2109 implant through the top surface of the silicon wafer to a selected depth, which defines the thickness of the material region, termed the thin film of material. As shown, the particles have a desired
 15 concentration 2111 at the selected depth (z_0). A variety of techniques can be used to implant the energetic particles into the silicon wafer. These techniques include ion implantation using, for example, beam line ion implantation equipment manufactured from companies such as Applied Materials, Eaton Corporation, Varian, and others. Alternatively, implantation occurs using a plasma immersion
 20 ion implantation ("PIII") technique. Of course, techniques used depend upon the application.

Depending upon the application, smaller mass particles are generally selected to reduce a possibility of damage to the material region. That is, smaller mass particles easily travel through the substrate material to the selected depth
 25 without substantially damaging the material region that the particles traversed through. For example, the smaller mass particles (or energetic particles) can be almost any charged (e.g., positive or negative) and/or neutral atoms or molecules, or electrons, or the like. In a specific embodiment, the particles can be neutral and/or charged particles including ions of hydrogen and its isotopes, rare gas ions
 30 such as helium and its isotopes, and neon. The particles can also be derived from compounds such as gases, e.g., hydrogen gas, water vapor, methane, and other hydrogen compounds, and other light atomic mass particles. Alternatively, the particles can be any combination of the above particles, and/or ions and/or

ions and/or molecular species and/or atomic species.

The process uses a step of joining the implanted silicon wafer to a workpiece or target wafer, as illustrated in Fig. 22. The workpiece may also be a variety of other types of substrates such as those made of a dielectric material (e.g., quartz, glass, silicon nitride, silicon dioxide), a conductive material (silicon, polysilicon, group III/V materials, metal), and plastics (e.g., polyimide-based materials). In the present example, however, the workpiece is a silicon wafer.

In a specific embodiment, the silicon wafers are joined or fused together using a low temperature thermal step. The low temperature thermal process generally ensures that the implanted particles do not place excessive stress on the material region, which can produce an uncontrolled cleave action. In one aspect, the low temperature bonding process occurs by a self-bonding process. In particular, one wafer is stripped to remove oxidation therefrom (or one wafer is not oxidized). A cleaning solution treats the surface of the wafer to form O-H bonds on the wafer surface. An example of a solution used to clean the wafer is a mixture of H_2O_2 - H_2SO_4 . A dryer dries the wafer surfaces to remove any residual liquids or particles from the wafer surfaces. Self-bonding occurs by placing a face of the cleaned wafer against the face of an oxidized wafer.

Alternatively, a self-bonding process occurs by activating one of the wafer surfaces to be bonded by plasma cleaning. In particular, plasma cleaning activates the wafer surface using a plasma derived from gases such as argon, ammonia, neon, water vapor, and oxygen. The activated wafer surface is placed against a face of the other wafer, which has a coat of oxidation thereon. The wafers are in a sandwiched structure having exposed wafer faces. A selected amount of pressure is placed on each exposed face of the wafers to self-bond one wafer to the other.

Alternatively, an adhesive disposed on the wafer surfaces is used to bond one wafer onto the other. The adhesive includes an epoxy, polyimide-type materials, and the like. Spin-on-glass layers can be used to bond one wafer surface onto the face of another. These spin-on-glass ("SOG") materials include, among others, siloxanes or silicates, which are often mixed with alcohol-based solvents or the like. SOG can be a desirable material because of the low temperatures (e.g., 150 to 250°C) often needed to cure the SOG after it is applied to surfaces of the

wafers.

Alternatively, a variety of other low temperature techniques can be used to join the donor wafer to the target wafer. For instance, an electro-static bonding technique can be used to join the two wafers together. In particular, one or both wafer surface(s) is charged to attract to the other wafer surface. Additionally, the donor wafer can be fused to the target wafer using a variety of commonly known techniques. Of course, the technique used depends upon the application.

After bonding the wafers into a sandwiched structure 2300, as shown in Fig. 23, the method includes a controlled cleaving action to remove the substrate material to provide a thin film of substrate material 2101 overlying an insulator 2305 the target silicon wafer 2201. The controlled-cleaving occurs by way of selective energy placement or positioning or targeting 2301, 2303 of energy sources onto the donor and/or target wafers. For instance, an energy impulse(s) can be used to initiate the cleaving action. The impulse (or impulses) is provided using an energy source which include, among others, a mechanical source, a chemical source, a thermal sink or source, and an electrical source.

The controlled cleaving action is initiated by way of any of the previously noted techniques and others and is illustrated by way of Fig. 23. For instance, a process for initiating the controlled cleaving action uses a step of providing energy 2301, 2303 to a selected region of the substrate to initiate a controlled cleaving action at the selected depth (z_0) in the substrate, whereupon the cleaving action is made using a propagating cleave front to free a portion of the substrate material to be removed from the substrate. In a specific embodiment, the method uses a single impulse to begin the cleaving action, as previously noted.

Alternatively, the method uses an initiation impulse, which is followed by another impulse or successive impulses to selected regions of the substrate. Alternatively, the method provides an impulse to initiate a cleaving action which is sustained by a scanned energy along the substrate. Alternatively, energy can be scanned across selected regions of the substrate to initiate and/or sustain the controlled cleaving action.

Optionally, an energy or stress of the substrate material is increased toward an energy level necessary to initiate the cleaving action, but not enough to initiate the cleaving action before directing an impulse or multiple successive

impulses to the substrate according to the present invention. The global energy state of the substrate can be raised or lowered using a variety of sources such as chemical, mechanical, thermal (sink or source), or electrical, alone or in combination. The chemical source can include particles, fluids, gases, or liquids.

5 These sources can also include chemical reaction to increase stress in the material region. The chemical source is introduced as flood, time-varying, spatially varying, or continuous. In other embodiments, a mechanical source is derived from rotational, translational, compressional, expansional, or ultrasonic energies. The mechanical source can be introduced as flood, time-varying, spatially varying, or
10 continuous. In further embodiments, the electrical source is selected from an applied voltage or an applied electro-magnetic field, which is introduced as flood, time-varying, spatially varying, or continuous. In still further embodiments, the thermal source or sink is selected from radiation, convection, or conduction. This thermal source can be selected from, among others, a photon beam, a fluid jet, a
15 liquid jet, a gas jet, an electro/magnetic field, a gas jet, an electron beam, a thermo-electric heating, and a furnace. The thermal sink can be selected from a fluid jet, a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a thermo-electric cooling means, an electro/magnetic field, and others. Similar to the previous embodiments, the thermal source is applied as flood, time-varying, spatially
20 varying, or continuous. Still further, any of the above embodiments can be combined or even separated, depending upon the application. Of course, the type of source used depends upon the application. As noted, the global source increases a level of energy or stress in the material region without initiating a cleaving action in the material region before providing energy to initiate the controlled cleaving
25 action.

In a preferred embodiment, the method maintains a temperature which is below a temperature of introducing the particles into the substrate. In some embodiments, the substrate temperature is maintained between -200 and 450°C during the step of introducing energy to initiate propagation of the cleaving
30 action. Substrate temperature can also be maintained at a temperature below 400°C or below 350°C. In preferred embodiments, the method uses a thermal sink to initiate and maintain the cleaving action, which occurs at conditions significantly below room temperature.

A final bonding step occurs between the target wafer and thin film of material region according to some embodiments, as illustrated by Fig. 24. In one embodiment, one silicon wafer has an overlying layer of silicon dioxide, which is thermally grown overlying the face before cleaning the thin film of material. The silicon dioxide can also be formed using a variety of other techniques, e.g., chemical vapor deposition. The silicon dioxide between the wafer surfaces fuses together thermally in this process.

In some embodiments, the oxidized silicon surface from either the target wafer or the thin film of material region (from the donor wafer) are further pressed together and are subjected to an oxidizing ambient 2401. The oxidizing ambient can be in a diffusion furnace for steam oxidation, hydrogen oxidation, or the like. A combination of the pressure and the oxidizing ambient fuses the two silicon wafers together at the oxide surface or interface 2305. These embodiments often require high temperatures (e.g., 700°C).

Alternatively, the two silicon surfaces are further pressed together and subjected to an applied voltage between the two wafers. The applied voltage raises temperature of the wafers to induce a bonding between the wafers. This technique limits the amount of crystal defects introduced into the silicon wafers during the bonding process, since substantially no mechanical force is needed to initiate the bonding action between the wafers. Of course, the technique used depends upon the application.

After bonding the wafers, silicon-on-insulator has a target substrate with an overlying film of silicon material and a sandwiched oxide layer between the target substrate and the silicon film, as also illustrated in Fig. 24. The detached surface of the film of silicon material is often rough 2404 and needs finishing. Finishing occurs using a combination of grinding and/or polishing techniques. In some embodiments, the detached surface undergoes a step of grinding using, for examples, techniques such as rotating an abrasive material overlying the detached surface to remove any imperfections or surface roughness therefrom. A machine such as a "back grinder" made by a company called Disco may provide this technique.

Alternatively, chemical mechanical polishing or planarization ("CMP") techniques finish the detached surface of the film, as illustrated by fig. 25.

In CMP, a slurry mixture is applied directly to a polishing surface 2501 which is attached to a rotating platen 2503. This slurry mixture can be transferred to the polishing surface by way of an orifice, which is coupled to a slurry source. The slurry is often a solution containing an abrasive and an oxidizer, e.g., H_2O_2 , KIO_3 , ferric nitrate. The abrasive is often a borosilicate glass, titanium dioxide, titanium nitride, aluminum oxide, aluminum trioxide, iron nitrate, cerium oxide, silicon dioxide (colloidal silica), silicon nitride, silicon carbide, graphite, diamond, and any mixtures thereof. This abrasive is mixed in a solution of deionized water and oxidizer or the like. Preferably, the solution is acidic.

This acid solution generally interacts with the silicon material from the wafer during the polishing process. The polishing process preferably uses a poly-urethane polishing pad. An example of this polishing pad is one made by Rodel and sold under the tradename of IC-1000. The polishing pad is rotated at a selected speed. A carrier head which picks up the target wafer having the film applies a selected amount of pressure on the backside of the target wafer such that a selected force is applied to the film. The polishing process removes about a selected amount of film material, which provides a relatively smooth film surface 2601 for subsequent processing, as illustrated by Fig. 26.

In certain embodiments, a thin film of oxide 2406 overlies the film of material overlying the target wafer, as illustrated in Fig. 29. The oxide layer forms during the thermal annealing step, which is described above for permanently bonding the film of material to the target wafer. In these embodiments, the finishing process is selectively adjusted to first remove oxide and the film is subsequently polished to complete the process. Of course, the sequence of steps depends upon the particular application.

In a specific embodiment, the silicon-on-insulator substrate undergoes a series of process steps for formation of integrated circuits thereon. These processing steps are described in S. Wolf, Silicon Processing for the VLSI Era (Volume 2), Lattice Press (1990), which is hereby incorporated by reference for all purposes. A portion of a completed wafer 2700 including integrated circuit devices is illustrated by Fig. 27. As shown, the portion of the wafer 2700 includes active devices regions 2701 and isolation regions 2703. The active devices are field effect transistors each having a source/drain region 2705 and a gate electrode 2707. A

dielectric isolation layer 2709 is defined overlying the active devices to isolate the active devices from any overlying layers.

In some embodiments, the present process can be used to form a multi-layered device structure 2800, such as the one illustrated by Fig. 28. This multi-layered device structure 2800 includes a layer 2801 of active devices in one layer and an overlying layer 2803 of active devices. A dielectric layer 2805 separates the lower layer of active devices from the upper layer of active devices. Another dielectric layer 2807 overlies the upper layer of active devices. The present controlled cleaving process may be used to form the multi-layered device structure of Fig. 28.

For example, a process according to the present invention for fabricating the multi-layer structure is defined as follows:

- (1) Provide a donor silicon wafer (which may be coated with a dielectric material);
- (2) Introduce particles into the silicon wafer to a selected depth to define a thickness of silicon film;
- (3) Provide a target substrate material (which may be coated with a dielectric material);
- (4) Bond the donor silicon wafer to the target substrate material by joining the implanted face to the target substrate material;
- (5) Increase global stress (or energy) of implanted region at selected depth without initiating a cleaving action (optional);
- (6) Provide stress (or energy) to a selected region of the bonded substrates to initiate a controlled cleaving action at the selected depth;
- (7) Provide additional energy to the bonded substrates to sustain the controlled cleaving action to free the thickness of silicon film from the silicon wafer (optional);
- (8) Complete bonding of donor silicon wafer to the target substrate;
- (9) Polish a surface of the thickness of silicon film;
- (10) Form active devices on thickness of silicon film;
- (11) Form dielectric layer overlying active devices; and
- (12) Repeat steps (1) to (11) above to form another layer of active devices on the target substrate material.

Alternatively, a process according to the present invention for fabricating the multi-layer structure is defined as follows:

- (1) Provide a donor silicon wafer having active devices thereon (which is coated with a dielectric material);
- 5 (2) Introduce particles into the silicon wafer to a selected depth to define a thickness of silicon film;
- (3) Provide a target substrate material (which may be coated with a dielectric material);
- (4) Bond the donor silicon wafer to the target substrate material by joining the implanted face to the target substrate material;
- 10 (5) Increase global stress (or energy) of implanted region at selected depth without initiating a cleaving action (optional);
- (6) Provide stress (or energy) to a selected region of the bonded substrates to initiate a controlled cleaving action at the selected depth;
- 15 (7) Provide additional energy to the bonded substrates to sustain the controlled cleaving action to free the thickness of silicon film from the silicon wafer (optional);
- (8) Complete bonding of donor silicon wafer to the target substrate;
- (9) Polish a surface of the thickness of silicon film; and
- 20 (10) Repeat steps (1) to (9) above to form another layer of active devices from another donor silicon wafer.

The above sequences of steps provide techniques for forming multi-layered structures by way of the present cleaving process. In one embodiment, the active devices are formed on the donor substrate before the present cleaving process. That is, the active devices are cleaved from the donor substrate. Additional donor substrates including devices may be used to form three-layered, four-layered, or greater-layered structures on the target substrate material. Alternatively, active devices are defined on the thin film of donor material defined on the target substrate. Additional donor substrate material may be added to the target substrate for creating three-layered, four-layered, or greater-layered structures. Accordingly, the present cleaving process provides for fabrication of multi-layered devices according to the present invention.

Although the above description is in terms of a silicon wafer, other substrates may also be used. For example, the substrate can be almost any monocrystalline, polycrystalline, or even amorphous type substrate. Additionally, the substrate can be made of III/V materials such as gallium arsenide, gallium nitride (GaN), and others. The multi-layered substrate can also be used according to the present invention. The multi-layered substrate includes a silicon-on-insulator substrate, a variety of sandwiched layers on a semiconductor substrate, and numerous other types of substrates. Additionally, the embodiments above were generally in terms of providing a pulse of energy to initiate a controlled cleaving action. The pulse can be replaced by energy that is scanned across a selected region of the substrate to initiate the controlled cleaving action. Energy can also be scanned across selected regions of the substrate to sustain or maintain the controlled cleaving action. One of ordinary skill in the art would easily recognize a variety of alternatives, modifications, and variations, which can be used according to the present invention.

While the above is a full description of the specific embodiments, various modifications, alternative constructions and equivalents may be used. Therefore, the above description and illustrations should not be taken as limiting the scope of the present invention which is defined by the appended claims.

WHAT IS CLAIMED IS:

- 1 1. A process for forming a film of material from a substrate, said
2 process comprising steps of:
3 introducing particles through a surface of a substrate to a selected
4 depth underneath said surface, said particles being at a concentration at said selected
5 depth to define a substrate material to be removed above said selected depth; and
6 providing energy to a selected region of said substrate to initiate a
7 controlled cleaving action at said selected depth in said substrate, whereupon said
8 cleaving action is made using a propagating cleave front to free a portion of said
9 material to be removed from said substrate.

- 1 2. The process of claim 1 wherein said particles are derived from
2 hydrogen gas, helium gas, water vapor, methane, and hydrogen compounds, and
3 other light atomic mass particles.

- 1 3. The process of claim 1 wherein said particles are selected
2 from the group consisting of neutral or charged molecules or atoms, or electrons.
3

- 4 4. The process of claim 1 wherein said particles are energetic.

- 1 5. The process of claim 4 wherein said energetic particles have
2 sufficient kinetic energy to penetrate through said surface to said selected depth
3 underneath said surface.

- 1 6. The process of claim 1 wherein said step of providing energy
2 sustains said controlled cleaving action to remove said material from said substrate
3 to provide a film of material.

- 1 7. The process of claim 1 wherein said step of providing energy
2 increases a controlled stress in said material and sustains said controlled cleaving
3 action to remove said material from said substrate to provide a film of material.

- 1 8. The process of claim 1 further comprising a step of providing

2 additional energy to said substrate to sustain said controlled cleaving action to
3 remove said material from said substrate to provide a film of material.

1 9. The process of claim 1 further comprising a step of providing
2 additional energy to said substrate to increases a controlled stress in said material
3 and sustains said controlled cleaving action to remove said material from said
4 substrate to provide a film of material.

1 10. The process of claim 1 wherein said introducing step forms
2 damage selected from atomic bond damage, bond substitution, weakening, or
3 breaking bonds of said substrate at said selected depth.

1 11. The process of claim 10 wherein said damage causes stress to
2 said substrate material.

1 12. The process of claim 10 wherein said damage reduces an
2 ability of said substrate material to withstand stress without a possibility of a
3 cleaving of said substrate material.

1 13. The process of claim 1 wherein said propagating cleave front
2 is selected from a single cleave front or multiple cleave fronts.

1 14. The process of claim 1 wherein said introducing step causes
2 stress of said material region at said selected depth by a presence of said particles at
3 said selected depth.

1 15. The process of claim 1 further comprising a step of increasing
2 an energy level of said substrate while substantially preventing a possibility of
3 cleaving said substrate.

1 16. The process of claim 15 wherein said step of introducing said
2 energy level is at a global substrate temperature that is below a temperature of said
3 introducing step.

1 17. The process of claim 1 further comprising a step of increasing
2 a stress of said substrate while substantially preventing a possibility of cleaving said
3 substrate at said selected depth.

1 18. The process of claim 17 wherein said step of introducing said
2 stress is maintained at a global substrate temperature that is below a temperature of
3 said introducing step.

1 19. The process of claim 15 wherein said step of increasing said
2 energy is performed while substantially preventing a possibility of inducing a
3 cleaving action between said film of material and said substrate.

1 20. The process of claim 15 wherein said step of increasing said
2 energy increases stress between said portion of said film material and said substrate
3 at said selected depth while substantially preventing a possibility of inducing a
4 cleaving action between said film of material and said substrate.

1 21. The process of claim 15 wherein said energy is selected from
2 a thermal source or sink, a mechanical source, a chemical source, and an electrical
3 source.

1 22. The process of claim 21 wherein said chemical source is
2 selected from particles, fluids, gases, or liquids.

1 23. The process of claim 21 wherein said chemical source includes
2 a chemical reaction.

1 24. The process of claim 21 wherein said chemical source is
2 flood, time-varying, spatially varying, or continuous.

1 25. The process of claim 21 wherein said mechanical source is
2 derived from a group selected from rotational, translational, compressional,
3 expansional, or ultrasonic.

1 26. The process of claim 21 wherein said mechanical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 27. The process of claim 21 wherein electrical source is selected
2 from an applied voltage or an applied electro-magnetic field.

1 28. The process of claim 21 wherein said electrical source is
2 flood, time-varying, spatially varying, or continuous.

1 29. The process of claim 21 wherein said thermal source or sink is
2 selected from radiation, convection, or conduction.

1 30. The process of claim 24 wherein said thermal source is
2 selected from a photon beam, a fluid jet, a liquid jet, a gas jet, an electro/magnetic
3 field, a gas jet, an electron beam, a thermo-electric heating, and a furnace.

1 31. The process of claim 29 wherein said thermal sink is selected
2 from a fluid jet, a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a
3 thermo-electric cooling means, and an electro/magnetic field.

1 32. The process of claim 21 wherein said thermal source or sink is
2 selected from flood, time-varying, spatially varying, or continuous.

1 33. The process of claim 1 wherein said energy is a thermal
2 source or sink, a mechanical source, a chemical source, and an electrical source.

1 34. The process of claim 33 wherein said chemical source is
2 provided by particles.

1 35. The process of claim 33 wherein said chemical source includes
2 a chemical reaction.

1 36. The process of claim 33 wherein said chemical source is

2 selected from flood, time-varying, spatially varying, or continuous.

1 37. The process of claim 33 wherein said mechanical source is
2 derived from a group selected from rotational, translational, compressional,
3 expansional, or ultrasonic.

1 38. The process of claim 33 wherein said mechanical source is
2 flood, time-varying, spatially varying, or continuous.

1 39. The process of claim 33 wherein electrical source is selected
2 from an applied voltage or an applied electro-magnetic means.

1 40. The process of claim 33 wherein said electrical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 41. The process of claim 33 wherein said thermal source or sink is
2 selected from radiation, convection, or conduction.

1 42. The process of claim 41 wherein said thermal source is
2 selected from a photon beam, a liquid jet, a gas jet, an electron beam, a thermo-
3 electric heating, and a furnace.

1 43. The process of claim 41 wherein said thermal sink is selected
2 from a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a thermo-
3 electric cooling means, and a super-cooled gas.

1 44. The process of claim 33 wherein said thermal source is
2 selected from flood, time-varying, spatially varying, or continuous.

45. The process of claim 1 wherein said substrate is maintained at
a temperature ranging between -200°C and 450°C during said introducing step.

1 46. The process of claim 1 wherein said step of providing said

2 energy is maintained at a temperature below 400°C.

1 47. The process of claim 1 wherein said step of providing said
2 energy is maintained at a temperature below 350°C.

1 48. The process of claim 1 wherein said step of introducing is a
2 step(s) of beam line ion implantation.

1 49. The process of claim 1 wherein said step of introducing is a
2 step(s) of plasma immersion ion implantation.

1 50. The process of claim 1 further comprising a step of joining
2 said surface of said substrate to a surface of a target substrate to form a stacked
3 assembly.

1 51. The process of claim 50 wherein said joining step is provided
2 by applying an electrostatic pressure between said substrate and said target
3 substrate.

1 52. The process of claim 50 wherein said joining step is provided
2 by using an adhesive substance between said target substrate and said substrate.

1 53. The process of claim 50 wherein said joining step is provided
2 by an activated surface between said target substrate and said substrate.

1 54. The process of claim 50 wherein said joining step is provided
2 by an interatomic bond between said target substrate and said substrate.

1 55. The process of claim 50 wherein said joining step is provided by
2 a spin-on-glass between said target substrate and said substrate.

1 56. The process of claim 50 wherein said joining step is provided
2 by a polyimide between said target substrate and said substrate.

1 57. The process of claim 1 wherein said substrate is made of a
2 material selected from silicon, diamond, quartz, glass, sapphire, silicon carbide,
3 dielectric, group III/V material, plastic, ceramic material, multi-layered substrate,
4 and processed wafer comprising active devices.

1 58. The process of claim 1 wherein said surface is planar.

1 59. The process of claim 1 wherein said surface is curved or
2 annular.

1 60. The process of claim 1 wherein said substrate is a silicon
2 substrate comprising an overlying layer of dielectric material, said selected depth
3 being underneath said dielectric material.

1 61. The process of claim 60 wherein said dielectric material is
2 selected from an oxide material, a nitride material, or an oxide/nitride material.

1 62. The process of claim 1 wherein said substrate includes an
2 overlying layer of conductive material.

1 63. The process of claim 62 wherein said conductive material is
2 selected from a metal, a plurality of metal layers, aluminum, tungsten, titanium,
3 titanium nitride, polycide, polysilicon, copper, indium tin oxide, silicide, platinum,
4 gold, silver, and amorphous silicon.

1 64. The process of claim 1 wherein said step of introducing
2 provides a substantially uniform distribution of particles along a plane of said
3 material region at said selected depth.

1 65. The process of claim 64 wherein said substantially uniform
2 distribution is a uniformity of less than about 5%.

1 66. The process of claim 1 wherein said introducing step provides
2 a patterned distribution of particles at said selected depth to enhance said controlled
3 cleaving action.

1 67. The process of claim 66 wherein said patterned distribution of
2 particles is selected from a checkerboard pattern, an annular ring pattern, a
3 concentric circle pattern, an annular pattern, a webbed pattern (e.g., dart board,
4 spider web), and spiral pattern defined on said top surface of said substrate.

1 68. The process of claim 1 wherein said substrate is re-used as a
2 donor substrate.

1 69. The process of claim 50 wherein said target substrate
2 undergoes fabrication steps for forming integrated circuits.

1 70. A process for forming a silicon-on-insulator substrate, said
2 process comprising steps of:
3 providing a donor substrate;
4 introducing particles through a surface of said donor substrate to a
5 selected depth underneath said surface, said particles being at a concentration at said
6 selected depth to define a substrate material to be removed above said selected
7 depth;
8 joining said donor substrate to a target substrate, said surface of said
9 donor substrate facing a face of said target substrate; and
10 providing energy to a selected region of said substrate to initiate a
11 controlled cleaving action at said selected depth in said substrate, whereupon said
12 cleaving action is made using a propagating cleave front to free a portion of said
13 substrate material to be removed from said substrate.

1 71. The process of claim 70 wherein said step of introducing is a
2 step(s) of beam line ion implantation.

1 72. The process of claim 70 wherein said step of introducing is a

2 step(s) of plasma immersion ion implantation.

1 73. The process of claim 70 wherein said particles are derived
2 from hydrogen gas, helium gas, water vapor, methane, and hydrogen compounds,
3 and other light atomic mass particles.

1 74. The process of claim 70 wherein said particles are selected
2 from the group consisting of neutral or charged molecules or atoms, or electrons.

1 75. The process of claim 70 wherein said particles are energetic.

1 76. The process of claim 75 wherein said energetic particles have
2 sufficient kinetic energy to penetrate through said surface to said selected depth
3 underneath said surface.

1 77. The process of claim 70 wherein said step of providing energy
2 sustains said controlled cleaving action to remove said substrate material from said
3 donor substrate to provide a film of material.

1 78. The process of claim 70 wherein said step of providing energy
2 increases a controlled stress in said substrate material and sustains said controlled
3 cleaving action to remove said substrate material from said donor substrate to
4 provide a film of material.

1 79. The process of claim 70 further comprising a step of providing
2 additional energy to said donor substrate to sustain said controlled cleaving action to
3 remove said substrate material from said donor substrate to provide a film of
4 material.

1 80. The process of claim 70 further comprising a step of providing
2 additional energy to said donor substrate to increase a controlled stress in said
3 substrate material and sustains said controlled cleaving action to remove said
4 substrate material from said donor substrate to provide a film of material.

1 81. The process of claim 70 wherein said introducing step forms
2 damage selected from the group consisting of atomic bond damage, bond
3 substitution, weakening, or breaking bonds of said donor substrate at said selected
4 depth.

1 82. The process of claim 81 wherein said damage causes stress to
2 said substrate material.

1 83. The process of claim 81 wherein said damage reduces an
2 ability of said substrate material to withstand stress without a possibility of a
3 cleaving of said substrate material.

1 84. The process of claim 70 wherein said expanding cleave front
2 is selected from a single cleave front or multiple cleave fronts.

1 85. The process of claim 70 wherein said introducing step causes
2 stress of said substrate material at said selected depth by a presence of said particles
3 at said selected depth.

1 86. The process of claim 70 further comprising a step of
2 increasing an energy level of said donor substrate while substantially preventing a
3 possibility of cleaving said substrate material at said selected depth.

1 87. The process of claim 86 wherein said step of introducing said
2 energy level is at a global substrate temperature that is below a temperature of said
3 introducing step.

1 88. The process of claim 70 further comprising a step of
2 increasing a stress of said substrate while substantially preventing a possibility of
3 cleaving said donor substrate at said selected depth.

1 89. The process of claim 88 wherein said step of introducing said

2 stress is maintained at a global substrate temperature that is below a temperature of
3 said introducing step.

1 90. The process of claim 86 wherein said step of increasing said
2 energy level is performed while substantially preventing a possibility of inducing a
3 cleaving action between said film of material and said donor substrate.

1 91. The process of claim 86 wherein said step of increasing said
2 energy increases stress between said portion of said film material and said donor
3 substrate at said selected depth while substantially preventing a possibility of
4 inducing a cleaving action between said film of material and said donor substrate.

1 92. The process of claim 86 wherein said energy level is provided
2 by a thermal source or sink, a mechanical source, a chemical source, and an
3 electrical source.

1 93. The process of claim 92 wherein said chemical source is
2 selected from particles, fluids, gases, or liquids.

1 94. The process of claim 92 wherein said chemical source includes
2 a chemical reaction.

1 95. The process of claim 93 wherein said chemical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 96. The process of claim 92 wherein said mechanical source is
2 derived from rotational, translational, compressional, expansional, or ultrasonic.

1 97. The process of claim 96 wherein said mechanical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 98. The process of claim 92 wherein electrical source is selected
2 from a group consisting of an applied voltage or an applied electro-magnetic field.

1 99. The process of claim 98 wherein said electrical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 100. The process of claim 92 wherein said thermal source or sink is
2 selected from radiation, convection, or conduction.

1 101. The process of claim 100 wherein said thermal source is
2 selected from a photon beam, a fluid jet, a liquid jet, a gas jet, an electro/magnetic
3 field, a gas jet, an electron beam, a thermo-electric heating, and a furnace.

1 102. The process of claim 100 wherein said thermal sink is selected
2 from a fluid jet, a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a
3 thermo-electric cooling means, and an electro/magnetic field.

1 103. The process of claim 100 wherein said thermal source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 104. The process of claim 1 wherein said energy is a thermal
2 source or sink, a mechanical source, a chemical source, and an electrical source.

1 105. The process of claim 104 wherein said chemical source is
2 provided by particles.

1 106. The process of claim 104 wherein said chemical source
2 includes a chemical reaction.

1 107. The process of claim 105 wherein said chemical source is
2 flood, time-varying, spatially varying, or continuous.

1 108. The process of claim 104 wherein said mechanical source is
2 derived from a group selected from rotational, translational, compressional,
3 expansional, or ultrasonic.

1 109. The process of claim 108 wherein said mechanical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 110. The process of claim 104 wherein electrical source is selected
2 from an applied voltage or an applied electro-magnetic means.

1 111. The process of claim 110 wherein said electrical source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 112. The process of claim 104 wherein said thermal source or sink
2 is selected from radiation, convection, or conduction.

1 113. The process of claim 112 wherein said thermal source is
2 selected from a photon beam, a liquid jet, a gas jet, an electron beam, a thermo-
3 electric heating, and a furnace.

1 114. The process of claim 112 wherein said thermal sink is selected
2 from a liquid jet, a gas jet, a cryogenic fluid, a super-cooled liquid, a thermo-
3 electric cooling means, and a super-cooled gas.

1 115. The process of claim 112 wherein said thermal source is
2 selected from flood, time-varying, spatially varying, or continuous.

1 116. The process of claim 70 wherein said donor substrate is
2 maintained at a temperature ranging between -200°C and 450°C during said
3 introducing step.

1 117. The process of claim 70 wherein said step of providing said
2 energy is maintained at a temperature below 400°C.

1 118. The process of claim 70 wherein said step of providing said
2 energy is maintained at a temperature below 350°C.

1 119. The process of claim 70 further comprising a step of removing
2 said substrate material to be removed from said donor substrate.

1 120. The process of claim 70 further comprising a step of treating
2 said target substrate comprising said jointed substrate material to bond said substrate
3 material to said target substrate.

1 121. The process of claim 120 wherein said step of treating is
2 selected from furnace annealing, thermal annealing, curing, and rapid thermal
3 annealing.

1 122. The process of claim 70 further comprising a step of treating
2 said target substrate comprising said jointed substrate material to bond said substrate
3 material to said target substrate.

1 123. The process of claim 122 wherein said step of treating is
2 selected from furnace annealing, thermal annealing, and rapid thermal annealing.

1 124. The process of claim 122 further comprising a step of
2 removing said substrate material to be removed from said donor substrate after said
3 treating step.

1 125. The process of claim 70 wherein said joining step comprises
2 activating said surface of said donor substrate to join said surface of said donor
3 substrate to said face of said target substrate.

1 126. The process of claim 70 wherein said joining step comprises
2 activating said surface of said donor substrate using a plasma process.

1 127. The process of claim 126 wherein said plasma process is
2 derived from gases selected from argon, ammonia, neon, water vapor, and oxygen.

1 128. The process of claim 70 wherein said joining step comprises

2 activating said surface of said donor substrate using a wet process.

1 129. The process of claim 128 wherein said wet process is derived
2 from a solution of hydrogen peroxide and sulfuric acid.

1 130. The process of claim 70 wherein said joining step comprises
2 activating said face of said target substrate to join said surface of said donor
3 substrate to said face of said target substrate.

1 131. The process of claim 130 wherein said joining step comprising
2 activating said face of said target substrate using a plasma process.

1 132. The process of claim 131 wherein said plasma process is
2 derived from gases selected from argon, ammonia, neon, water vapor, and oxygen.

1 133. The process of claim 70 wherein said joining step comprising
2 activating said face of said target substrate using a wet process.

1 134. The process of claim 133 wherein said wet process is derived
2 from a solution of hydrogen peroxide and sulfuric acid.

1 135. The process of claim 70 wherein said joining step is provided
2 by applying an electrostatic pressure between said target substrate and said donor
3 substrate.

1 136. The process of claim 70 wherein said joining step is provided
2 by using an adhesive substance between said target substrate and said donor
3 substrate.

1 137. The process of claim 70 wherein said joining step is provided
2 by an interatomic bond between said target substrate and said donor substrate.

1 138. The process of claim 70 wherein said joining step is provided

2 by a spin-on-glass between said target substrate and said donor substrate.

1 139. The process of claim 70 wherein said joining step is provided
2 by a polyimide film between said target substrate and said donor substrate.

1 140. The process of claim 70 further comprising a step of finishing
2 a surface of said material.

1 141. The process of claim 140 wherein said finishing step is a
2 polishing step.

1 142. The process of claim 140 wherein said finishing step is a
2 chemical mechanical polishing step.

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A CONTROLLED CLEAVAGE PROCESS AND RESULTING DEVICE

ABSTRACT OF THE DISCLOSURE

A technique for forming a film of material (12) from a donor
5 substrate (10). The technique has a step of introducing energetic particles (22)
through a surface of a donor substrate (10) to a selected depth (20) underneath the
surface, where the particles have a relatively high concentration to define a donor
substrate material (12) above the selected depth. An energy source is directed to a
selected region of the donor substrate to initiate a controlled cleaving action of the
10 substrate (10) at the selected depth (20), whereupon the cleaving action provides an
expanding cleave front to free the donor material from a remaining portion of the
donor substrate.

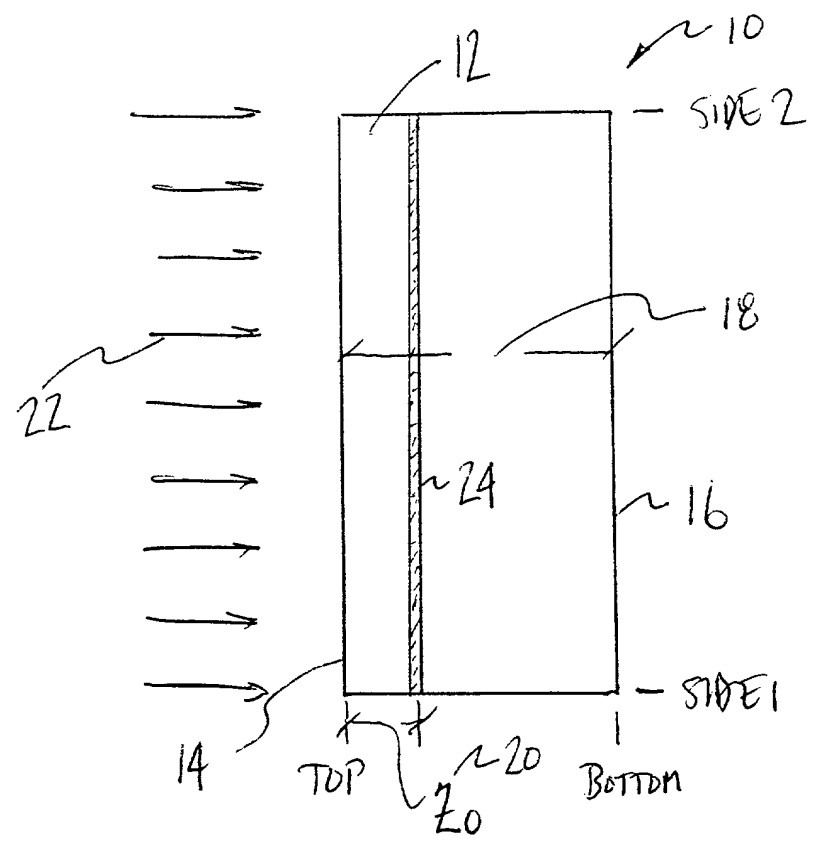


FIG. 1

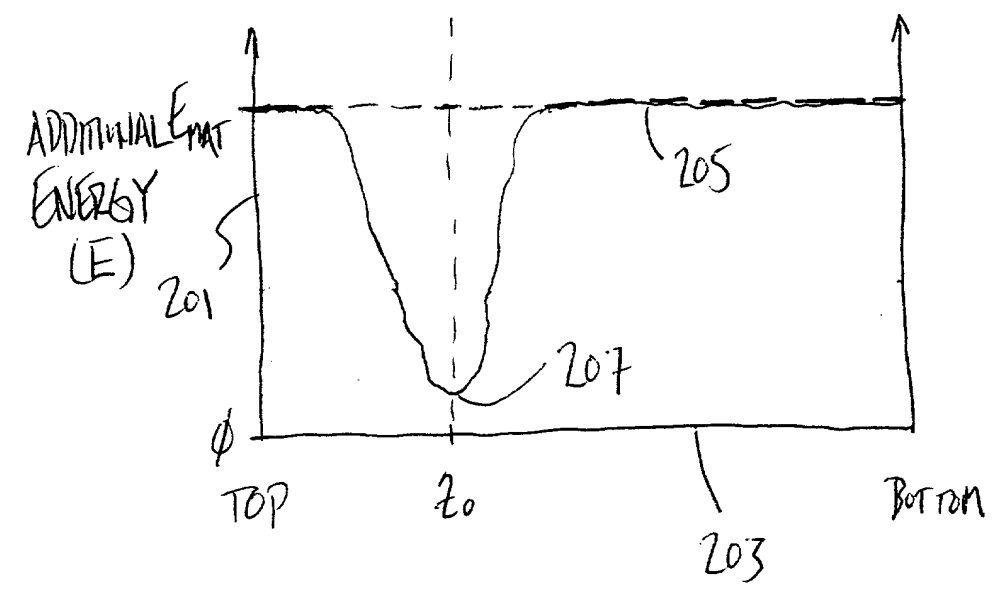


FIG. 2

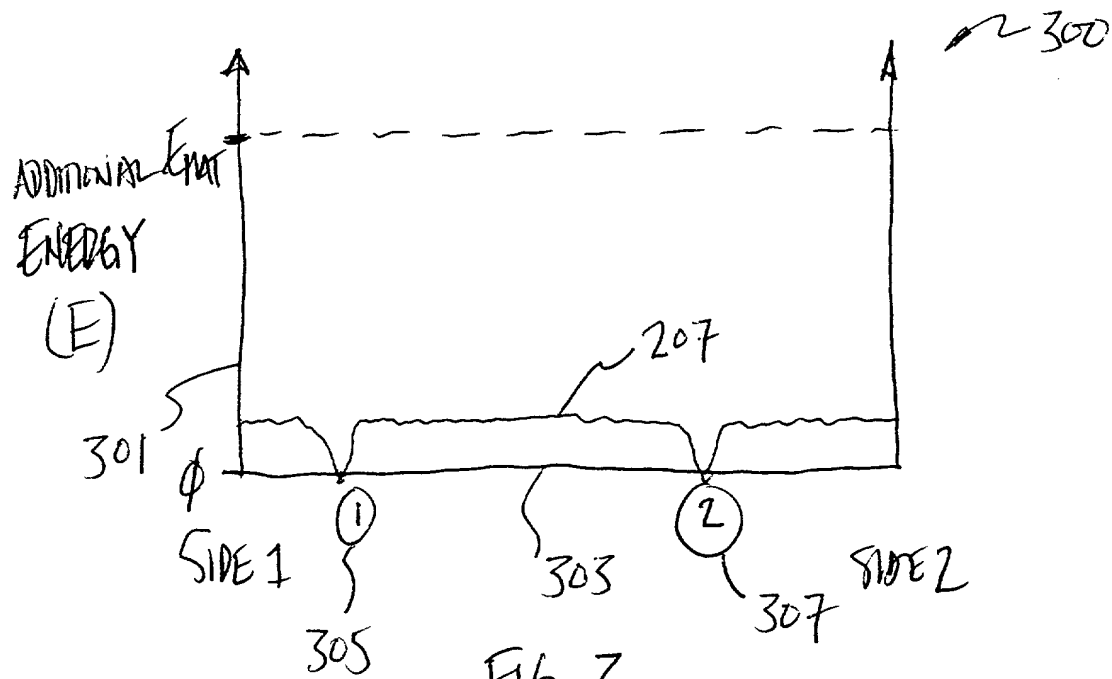


FIG. 3

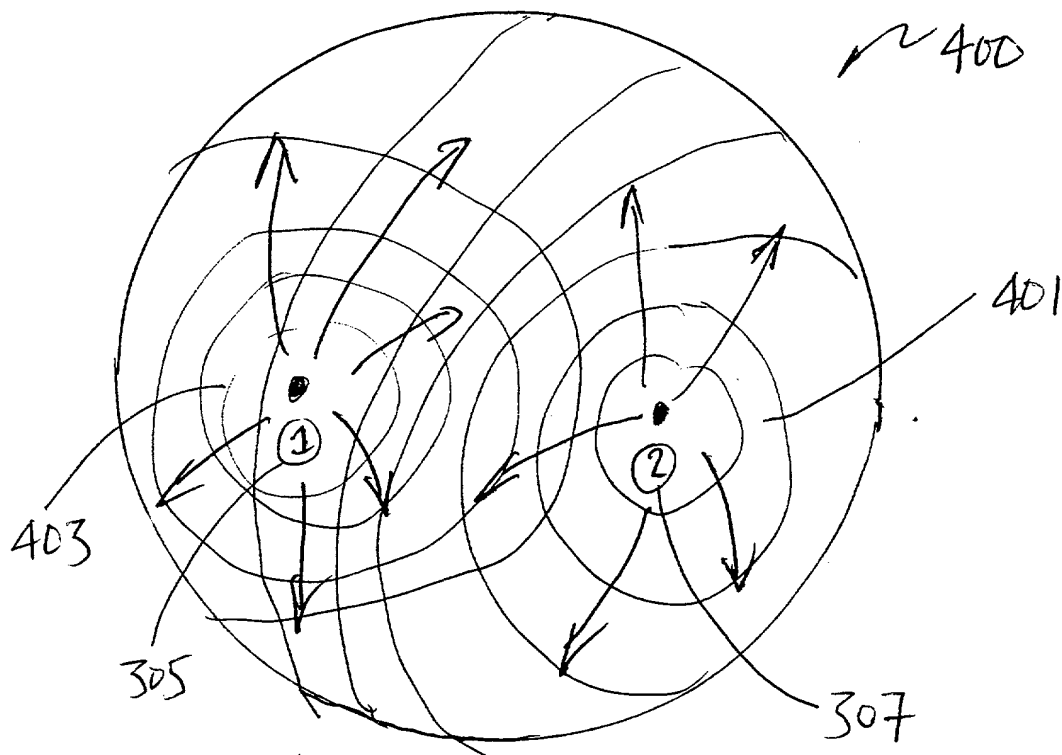


FIG. 4

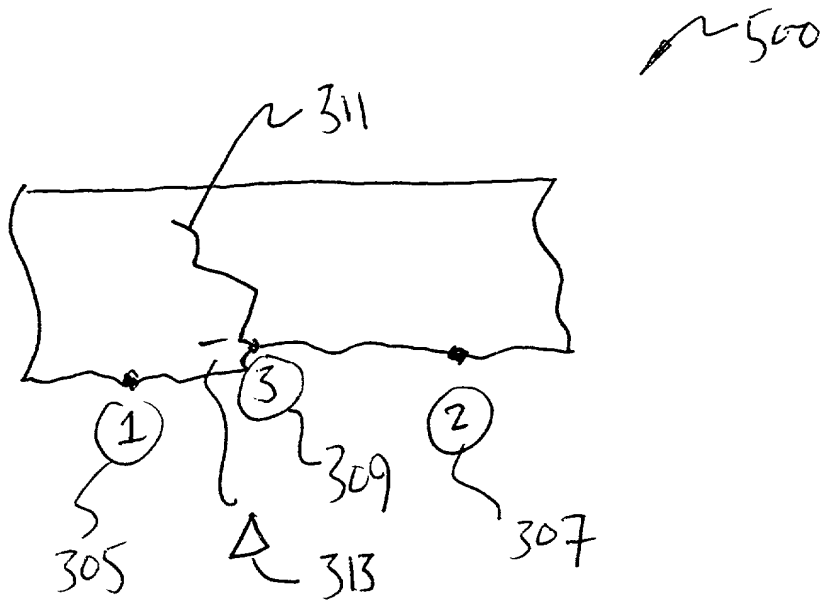
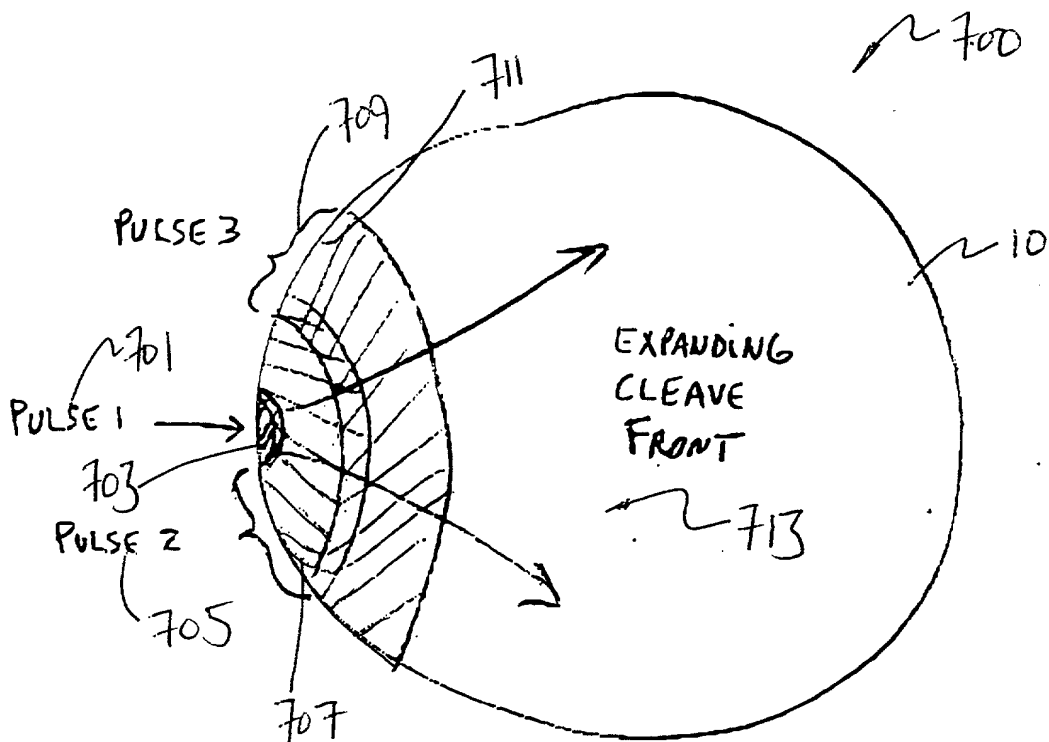
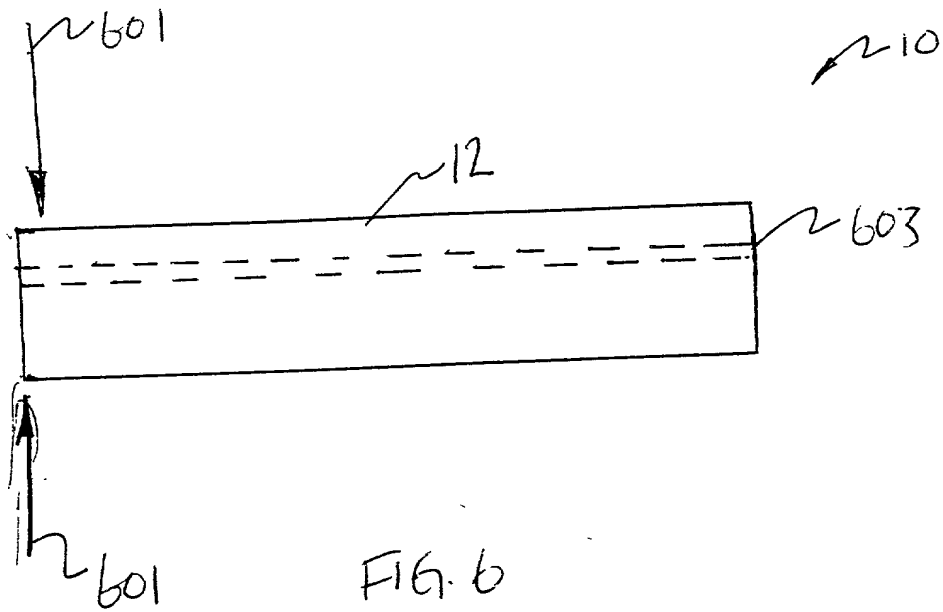


Fig. 5



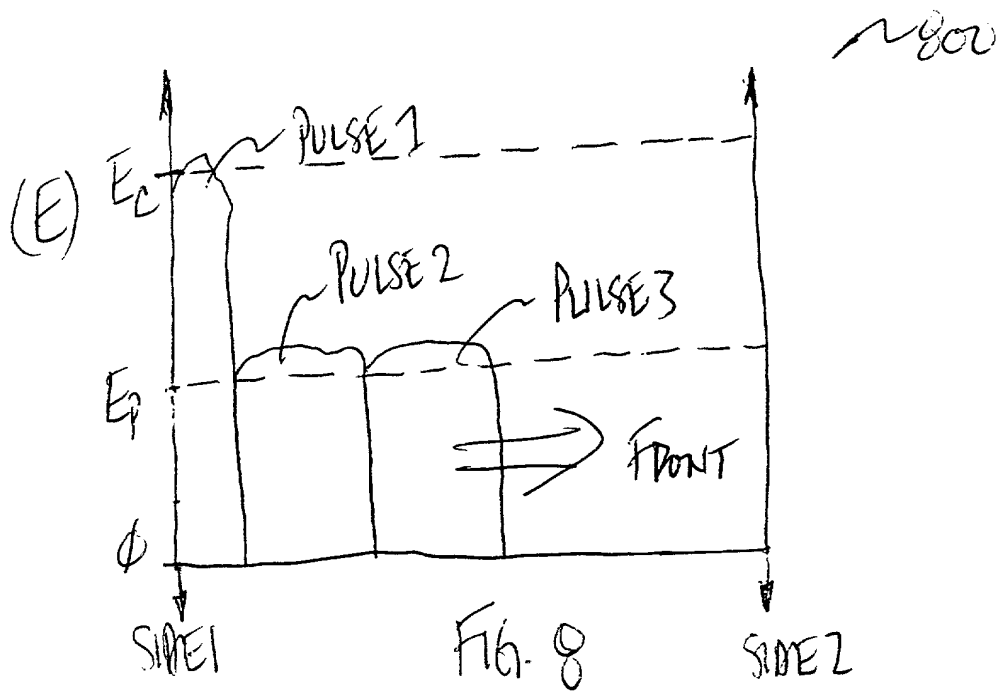


Fig. 8

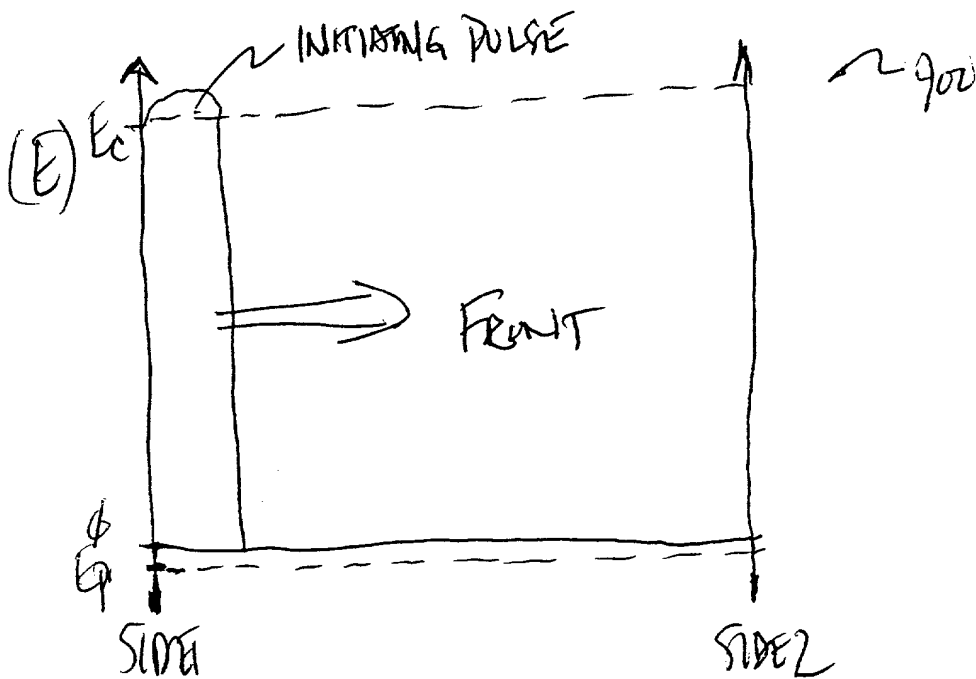
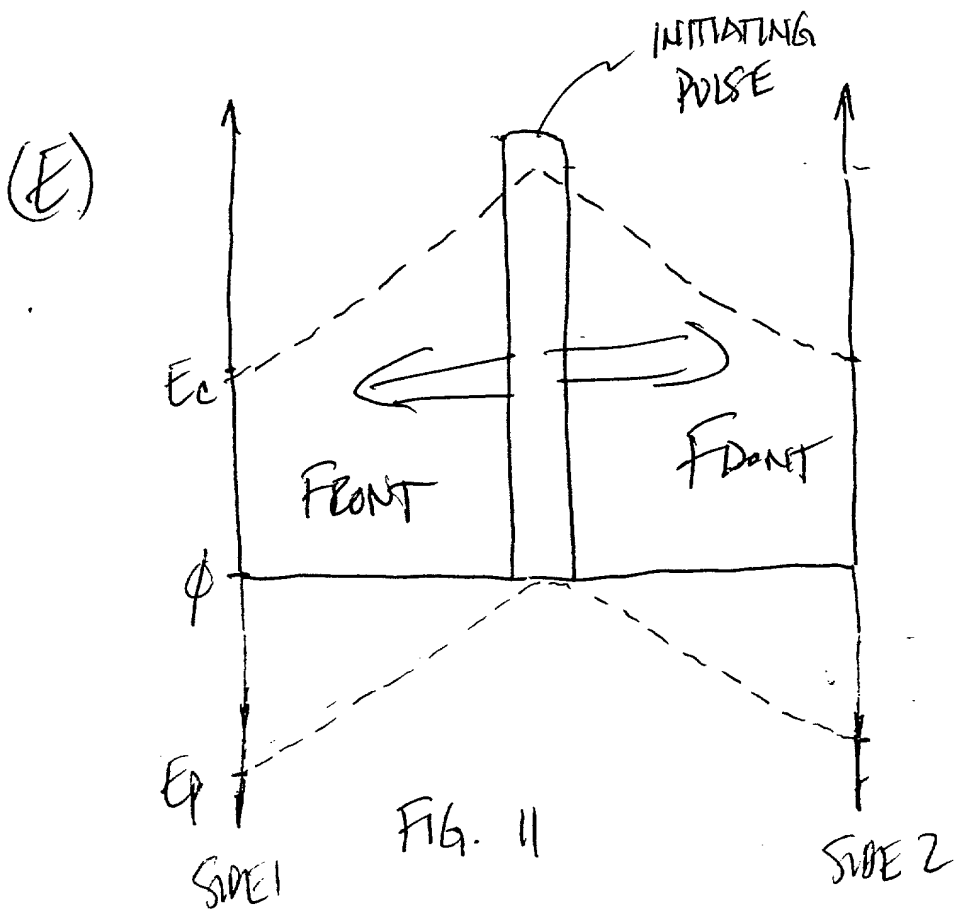
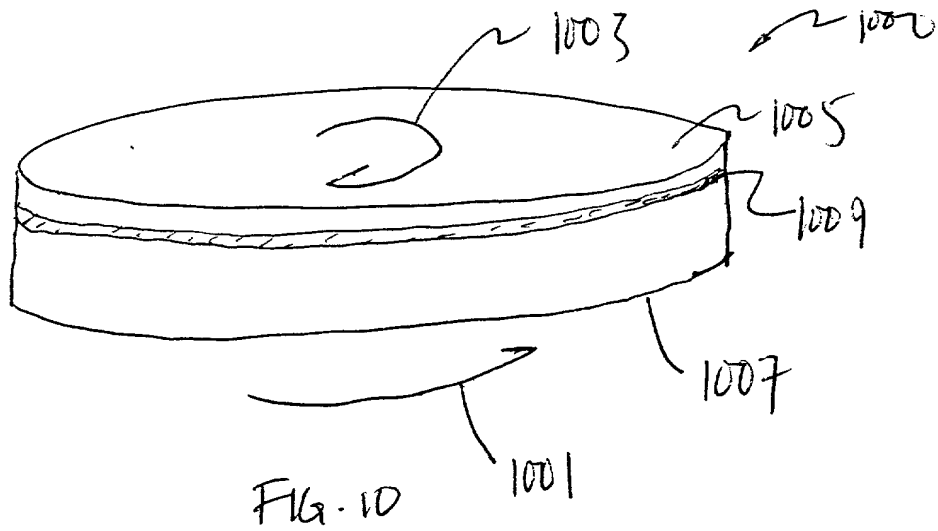
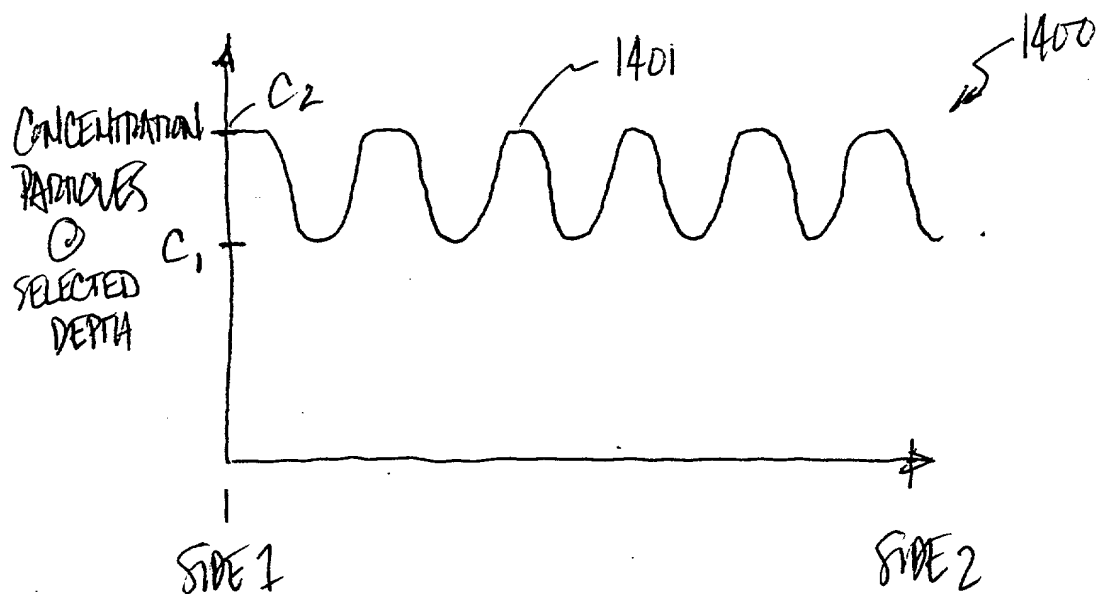
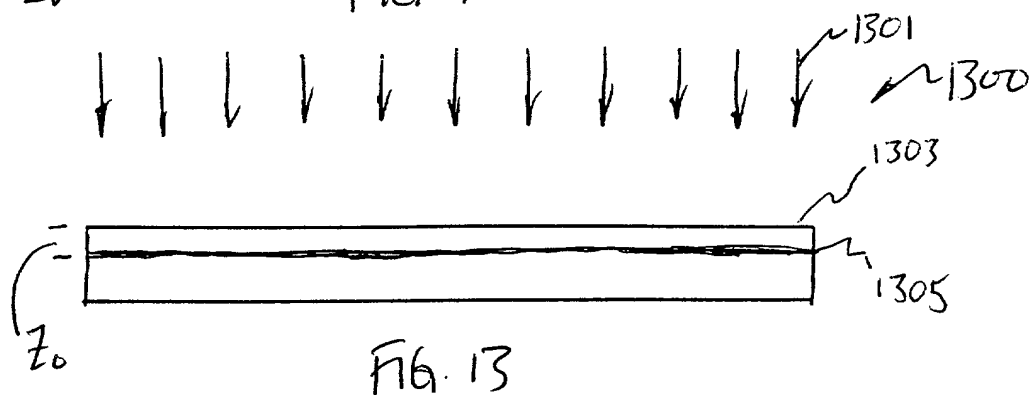
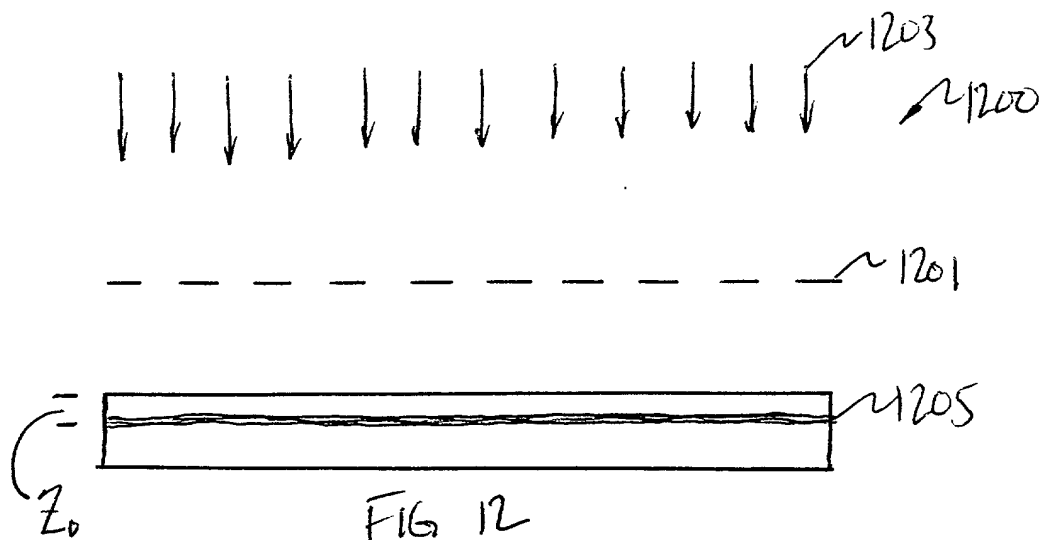


Fig. 9





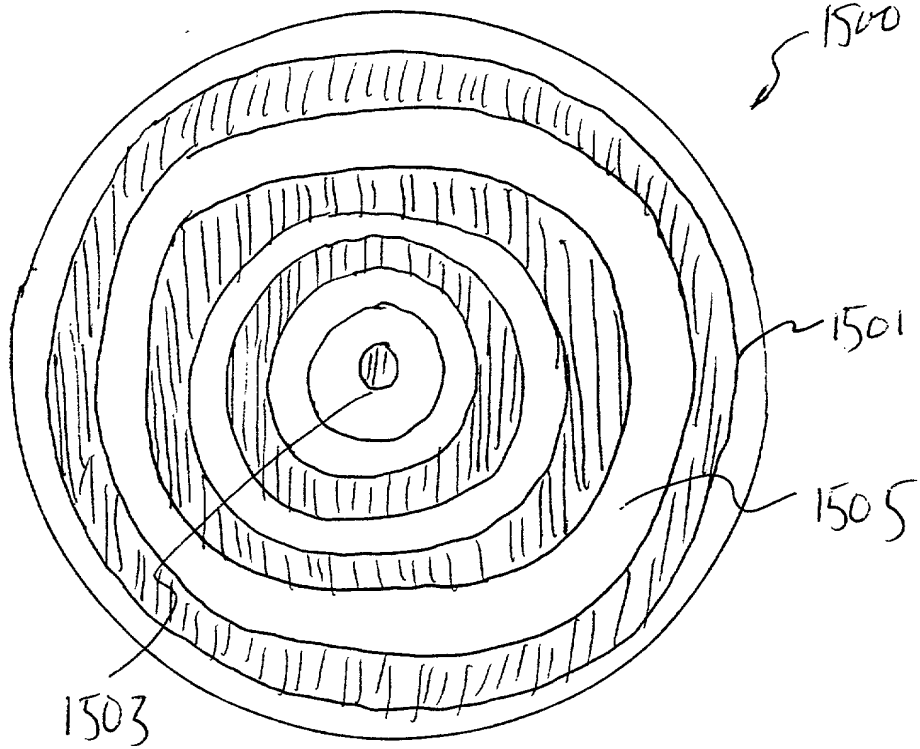


FIG. 15

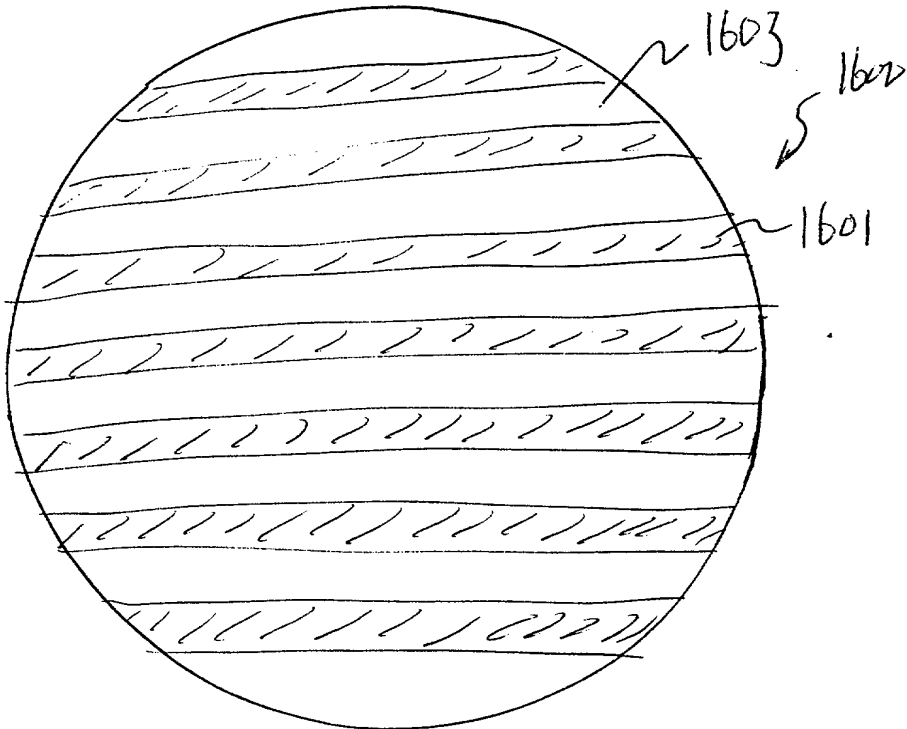


FIG. 16

46 50 54 58 62 66 70 74 78 82 86 90 94 98 102 106 110 114 118 122 126 130 134 138 142 146 150 154 158 162 166 170 174 178 182 186 190 194 198 202 206 210 214 218 222 226 230 234 238 242 246 250 254 258 262 266 270 274 278 282 286 290 294 298 302 306 310 314 318 322 326 330 334 338 342 346 350 354 358 362 366 370 374 378 382 386 390 394 398 402 406 410 414 418 422 426 430 434 438 442 446 450 454 458 462 466 470 474 478 482 486 490 494 498 502 506 510 514 518 522 526 530 534 538 542 546 550 554 558 562 566 570 574 578 582 586 590 594 598 602 606 610 614 618 622 626 630 634 638 642 646 650 654 658 662 666 670 674 678 682 686 690 694 698 702 706 710 714 718 722 726 730 734 738 742 746 750 754 758 762 766 770 774 778 782 786 790 794 798 802 806 810 814 818 822 826 830 834 838 842 846 850 854 858 862 866 870 874 878 882 886 890 894 898 902 906 910 914 918 922 926 930 934 938 942 946 950 954 958 962 966 970 974 978 982 986 990 994 998

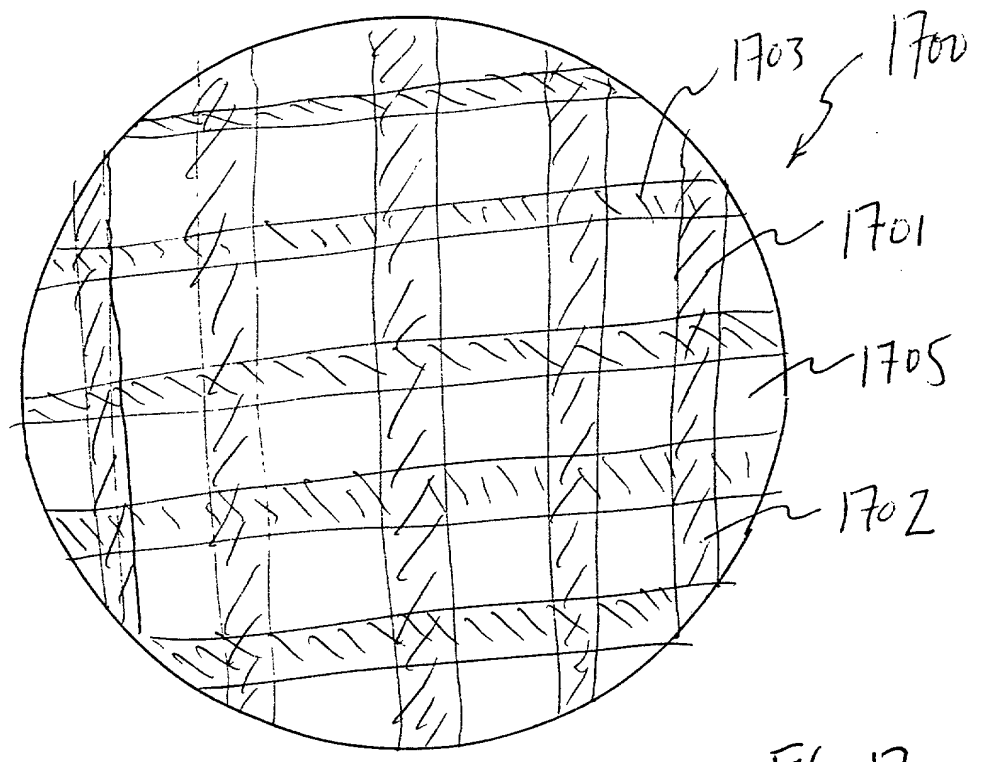


FIG. 17

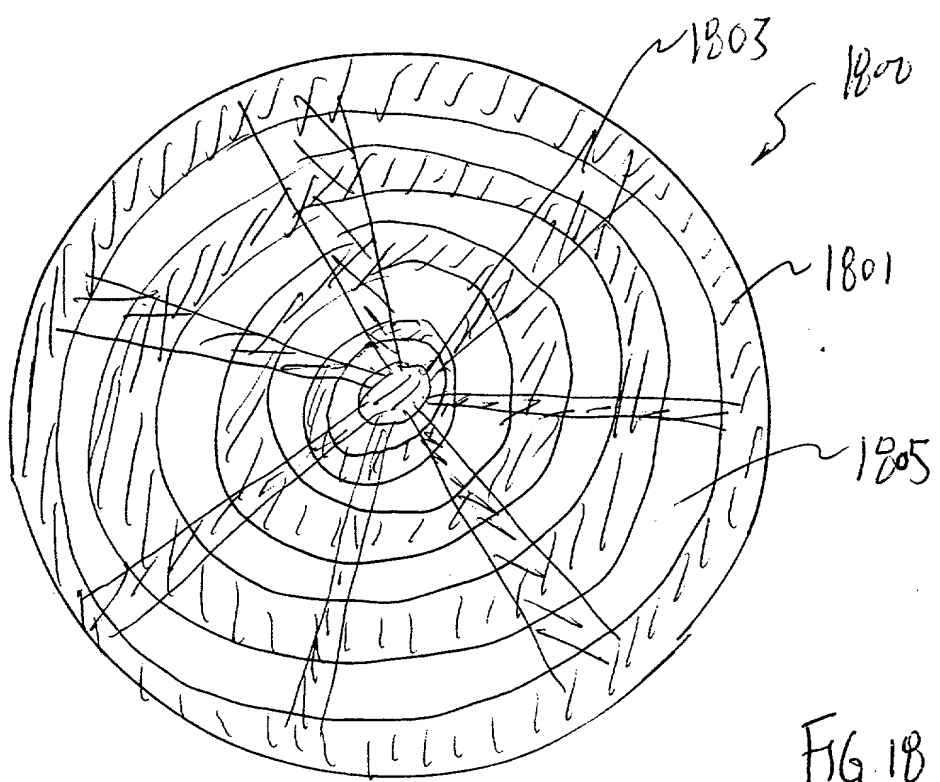


FIG. 18

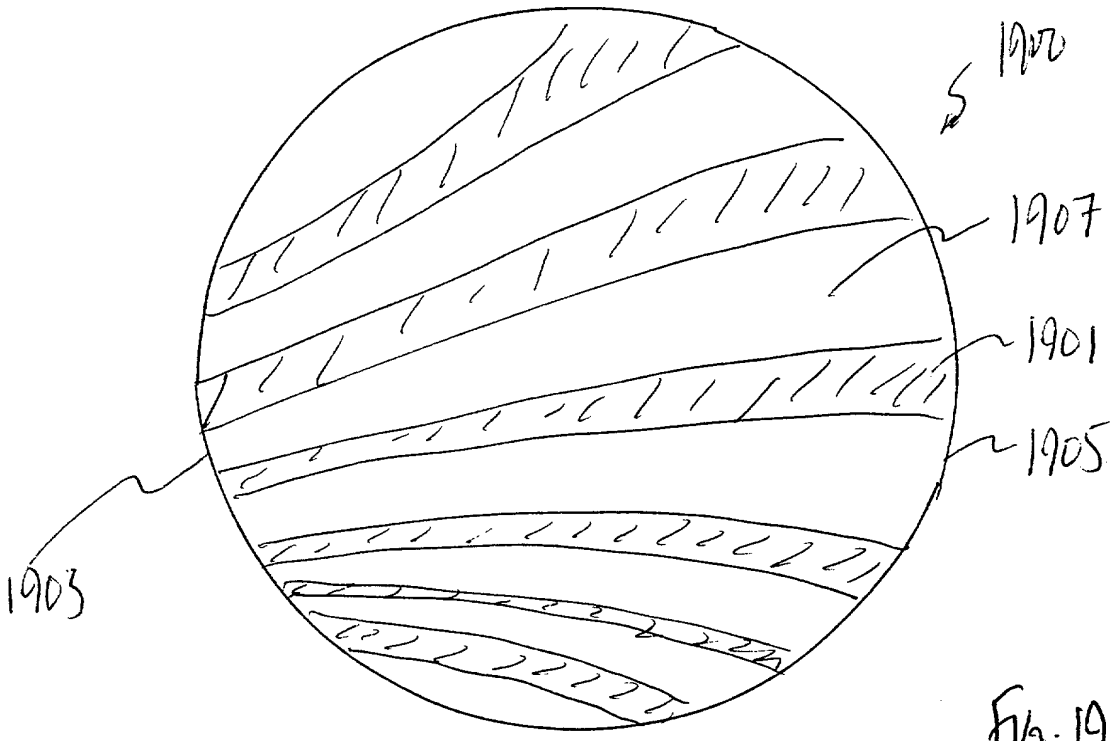


Fig. 19

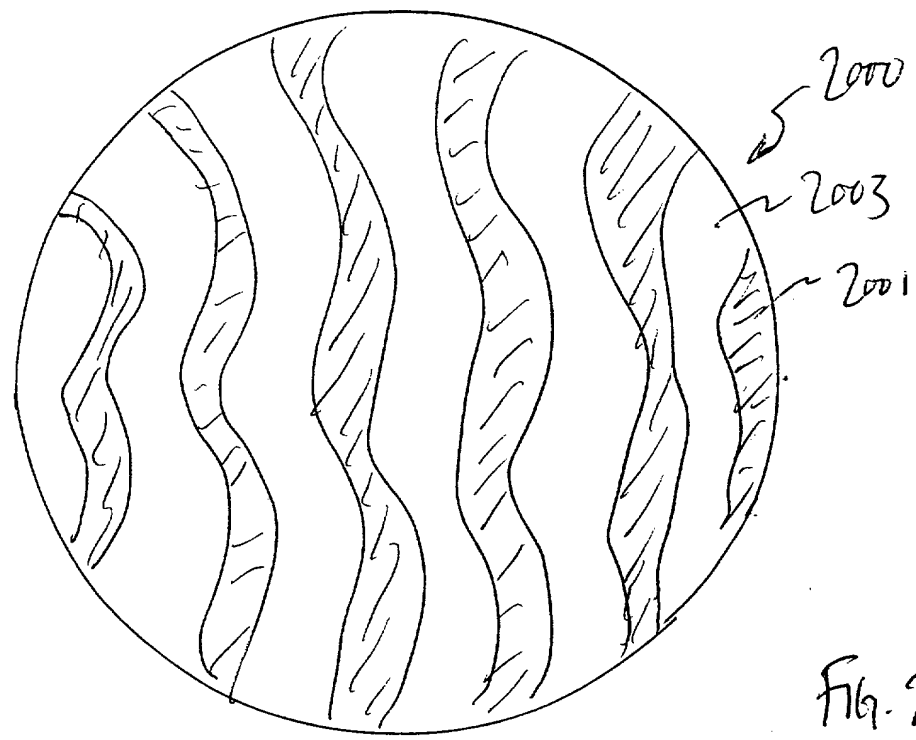


Fig. 20

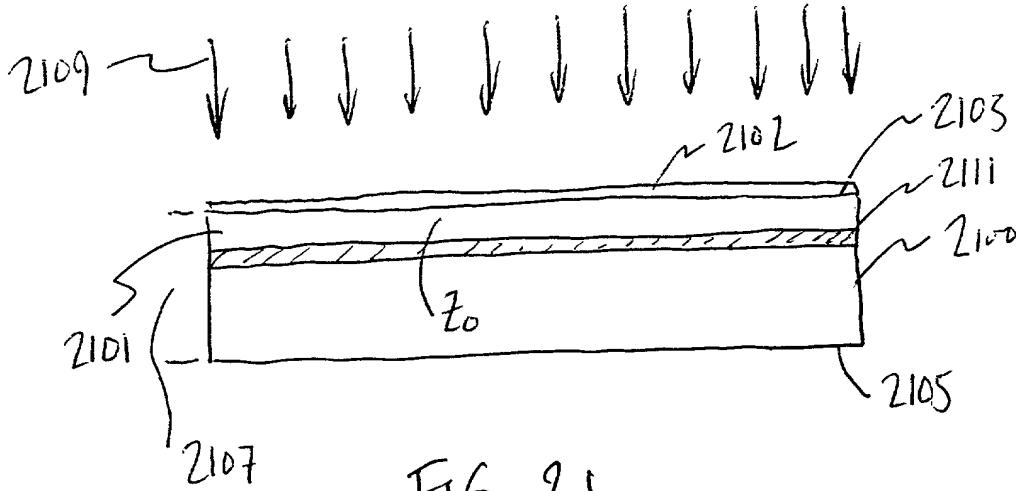


FIG. 21

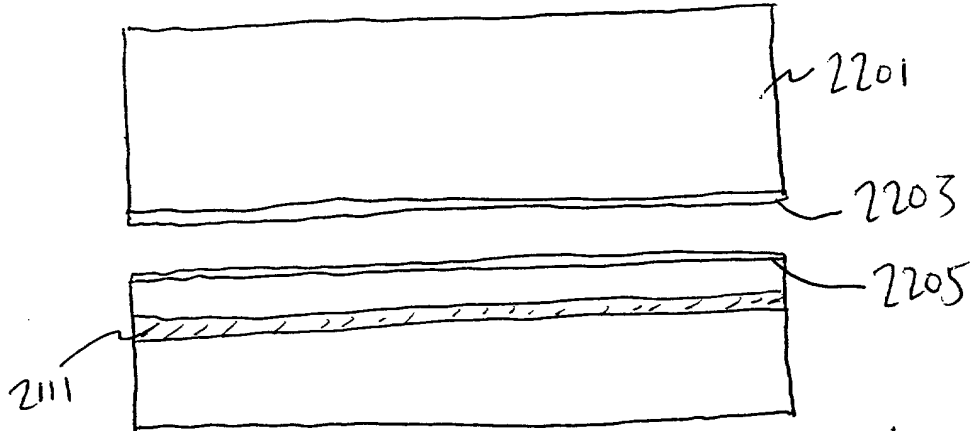
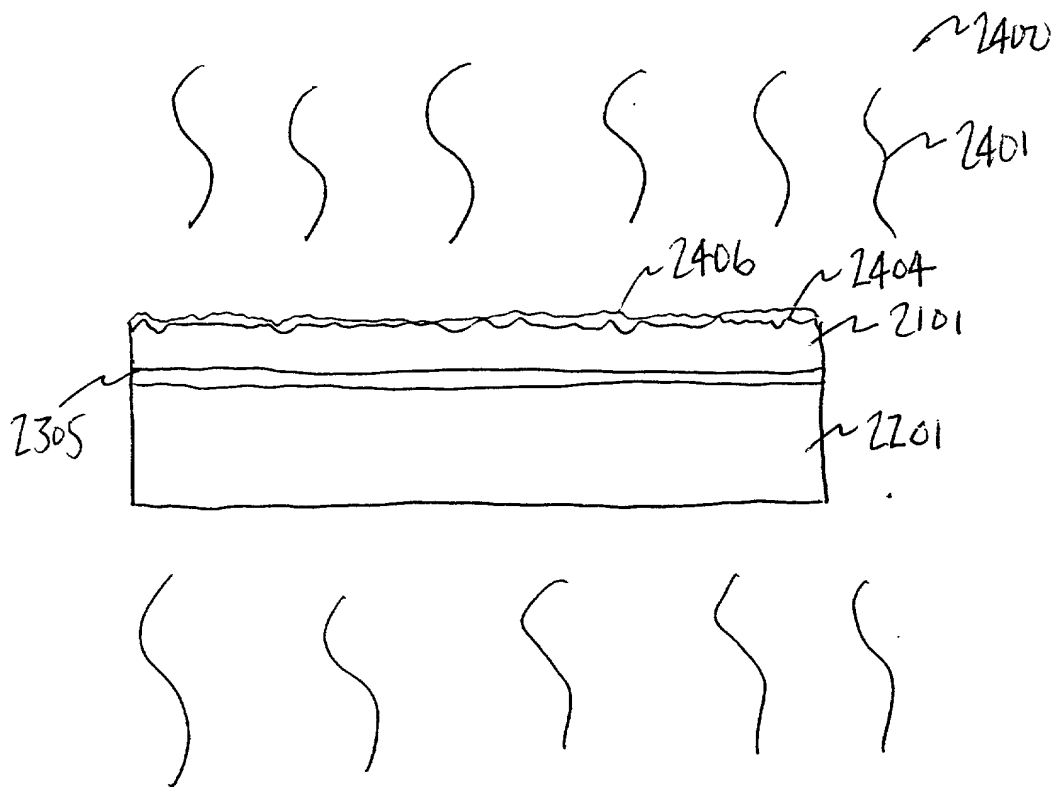
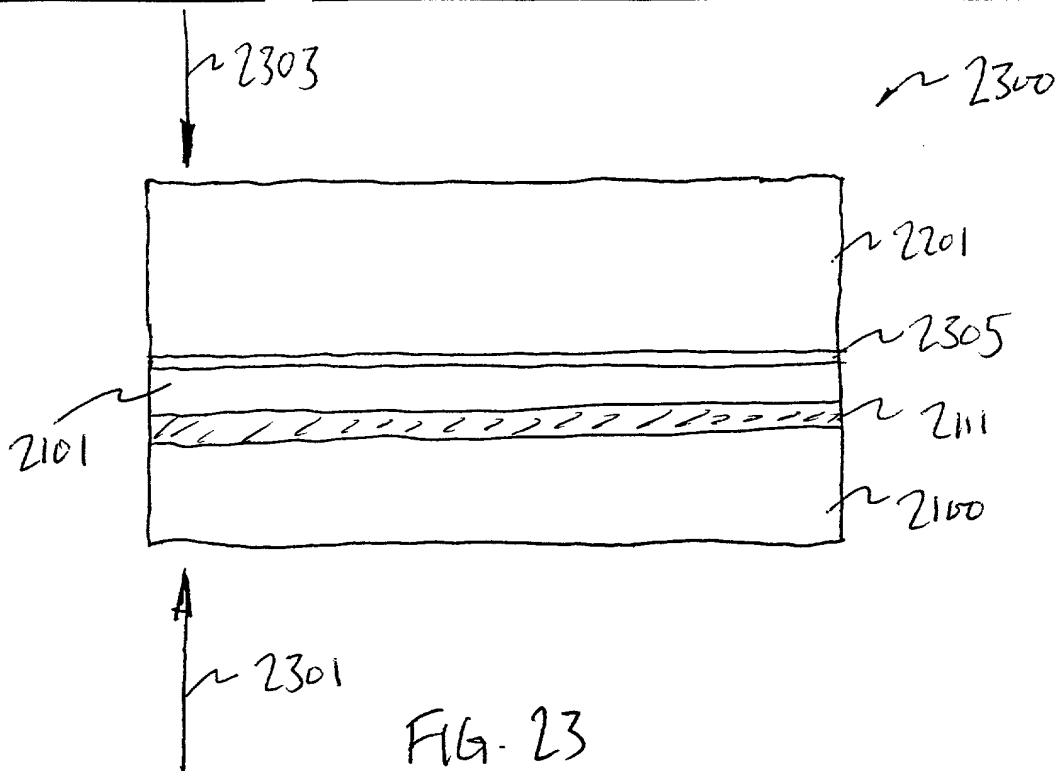


FIG. 22



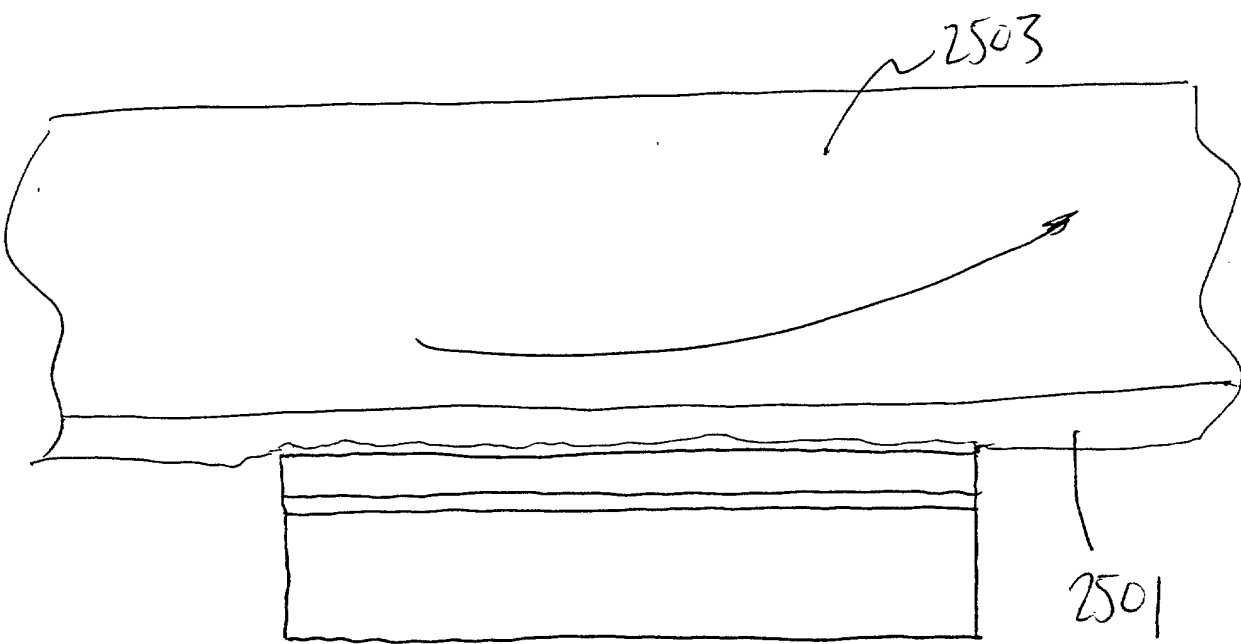


FIG. 25

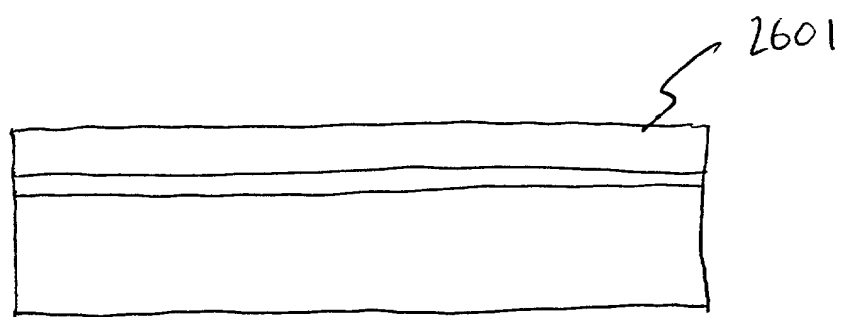


FIG. 26

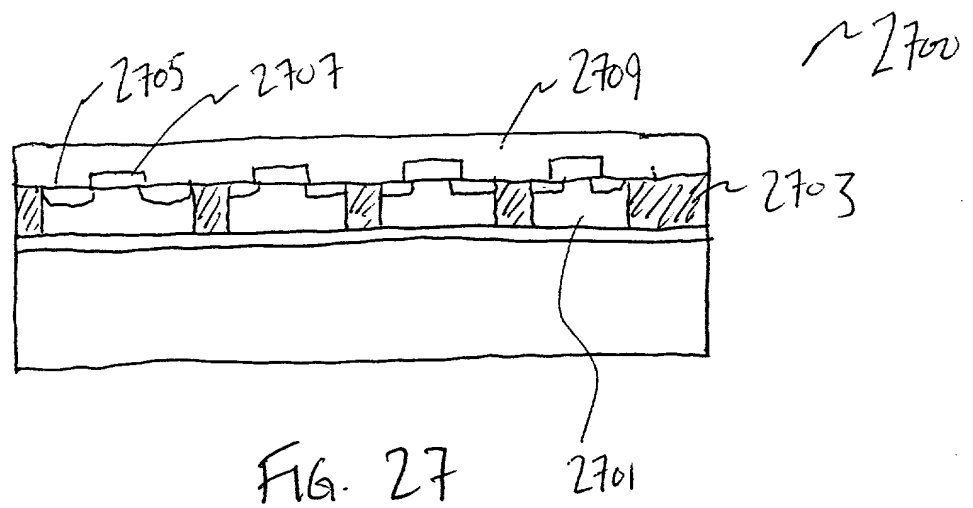


FIG. 27

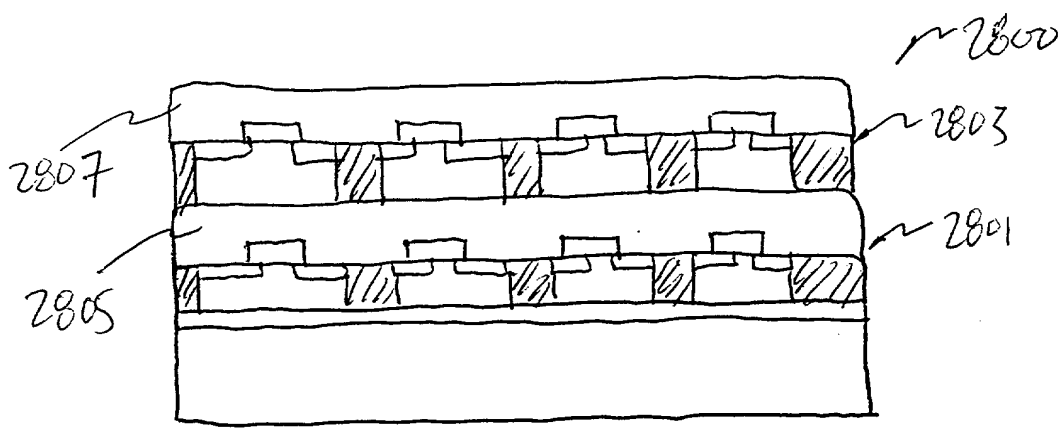


FIG. 28