

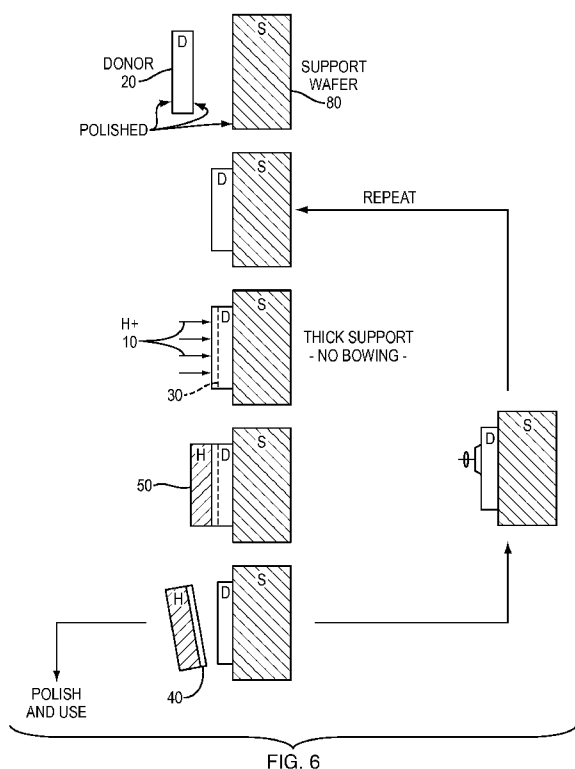


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[Continued on next page]

(54) **Title:** SUPPORT SUBSTRATE FOR ION BEAM EXFOLIATION OF A CRYSTALLINE LAMINA

(57) **Abstract:** The disclosed embodiments relate to techniques for supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina. According to embodiments of the disclosure, a donor substrate of crystalline material is provided having a front surface and a back surface, and a support substrate is provided such that the back surface of the donor substrate can be bonded to the support substrate. As such, an ion dosage may be implanted to the front surface of the donor substrate to form a cleave plane within the donor substrate, thereby forming an implanted composite material. Consequently, a crystalline lamina may be cleaved from the donor substrate along the cleave plane, while the back surface remains bonded to the support substrate.

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TITLE**SUPPORT SUBSTRATE FOR ION BEAM EXFOLIATION
OF A CRYSTALLINE LAMINA****CROSS-REFERENCE TO RELATED APPLICATION**

The present application claims the benefit of U.S. Patent Application No. 62/023,514 filed July 11, 2014, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION**1. Field of the Invention.**

[0001] The present invention relates to supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina.

2. Description of the Related Art.

[0002] Ion implantation is a materials engineering process by which ions of a source material are accelerated in an electrical field and impacted into a solid target substrate. This process is used to change the physical, chemical, or electrical properties of the solid. Ion implantation is often used in semiconductor device fabrication and in metal finishing, as well as various applications in materials science. Ion implantation equipment typically consists of an ion source, where ions of the desired element are produced, an accelerator, where the ions are accelerated to a specific energy, and a target chamber, where the ions impinge on a target, which is the material to be implanted. The energy of the ions, as well as the ion species and the composition of the target, determine the depth of penetration of the ions in the solid, i.e., the “range” of the ions.

[0003] There are various uses for ion implantation, such as the introduction of dopants (e.g., boron, phosphorus or arsenic) in a semiconductor. For instance, modification of

semiconductors such as silicon wafers is often implemented by ion implanters, where a surface is uniformly irradiated by a beam of ions or molecules, of a specific species and prescribed energy. Another use for ion implantation is for cleaving (exfoliating) thin sheets (lamina) of hard crystalline materials such as silicon, sapphire, etc. As shown in FIG 1, generally, this process involves implanting light ions 10 into a donor substrate 20 where they will stop below the surface in a layer in a “cleave plane” 30. The material may then be heated (for example), causing the material above the implanted layer to cleave off or exfoliate in a sheet or lamina 40.

[0004] In some cases, it is desirable to use a thicker “handle” substrate to provide mechanical support for the lamina, and bonding to the support can occur either before or after exfoliation. For example, a bond (e.g., temporary or permanent) may be created with the donor substrate (at the portion that will become lamina) before the cleaving, thereby forming a composite structure. When cleaving (exfoliating) the lamina from the donor substrate, both the lamina and the backing substrate/handle are cleaved from the substrate. Bonding before exfoliation is particularly advantageous for very thin, delicate lamina to assist in subsequent handling and processing steps.

[0005] In particular, for many materials such as semiconductor and optical substrates the cost of the bulk material is very high, while its functional value resides mostly in the surface or in a thin layer very near the surface. For example, materials such as mono-crystalline silicon carbide (cSiC) and mono-crystalline aluminum nitride (cAlN) are used in LEDs and power semiconductors, and, in these applications, the crystalline surface provides a template for epitaxial growth of other materials, whereas the bulk does little more than provide mechanical support. Thus, a target of ion beam induced layer transfer is to obtain very thin layers of the costly crystalline material with minimum waste. A lower-cost substrate (handle) such as a multi-crystalline form of the same material (mSiC, mAlN, etc.) or other handle material of similar thermal expansion characteristics can also be attached prior to exfoliation to provide additional support to the resulting lamina. In this way overall cost is reduced.

[0006] FIG. 2 illustrates such a process where: 1) a relatively thicker wafer of the expensive (“\$\$\$”) mono-crystalline “donor” material 20 is provided (e.g., with a polished surface), 2) the donor is implanted with ions 10 to form cleave plane (implanted layer) 30, 3) the

implanted face is bonded to a “handle” wafer 50 (generally less expensive “\$”), and 4) the bonded pair is cleaved (exfoliated) leaving a thin layer of the mono-crystalline material (lamina 40) attached to the handle along with a remnant donor 20R. After cleaving, 5) the newly exposed cleaved surfaces on both the laminated stack and the remnant donor may be polished to produce high quality surfaces, and 6) the process can be repeated from step 1 using remnant donor wafer 20R. In this way the expensive donor is progressively sliced from its starting thickness until it reaches its “minimum thickness” and is too thin to be reused.

[0007] This minimum thickness, as illustrated in more detail in FIG. 3, represents waste material that cannot be further sliced and must be recycled. It is desirable to minimize the fraction of material that is wasted in this manner. On the other hand a large starting thickness is also undesirable since it represents a larger value placed at risk in the process equipment and a larger investment in WIP (work-in-process). There can also be problems cooling thick substrates during implant due to the temperature gradient through the material.

[0008] Still another problem is that the ion beam implantation - usually at high doses - introduces compressive stress into the implanted surface as a result of the introduction of interstitial hydrogen ions and damage to the crystal lattice. As shown in FIGS. 4A-4B, the implanted layer naturally tends to expand relative to the un-implanted material, causing the wafer to bow away from the implanted side. Subsequent bonding of the implanted face to a handle wafer is made difficult due to the bowing.

[0009] Finally, as shown in FIGS. 5A-5B, obtaining multiple layers from one donor substrate requires excessive handling of the valuable donor wafer, supported at its edges, which risks chipping or otherwise damaging those edges. The process of cleaving brittle materials is sensitive to the condition of the wafer edges, as they can be a source of fracture initiation. Generally edges must remain in good condition throughout the multiple cycles of ion beam cleaving. Furthermore, supporting the donor wafer directly (during implantation for example) may cool the wafer locally at the points where it contacts the support, thereby producing inconsistent cleaving results. Further still, supporting the donor wafer directly at the edges during implantation can lead to “shadowing” of regions of the donor from the ion beam, which can cause incomplete exfoliation and is therefore highly undesirable.

SUMMARY OF THE INVENTION

[00010] The disclosed embodiments relate to techniques for supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina. In particular, by adding a back-side support substrate to the donor material during processing of the donor material, the problems mentioned above may be reduced or alleviated. For instance, during the processing (e.g., ion implanting and/or cleaving), bowing of the donor material may be prevented, and, furthermore, the donor material may be almost completely utilized through repeated exfoliations. Moreover, the techniques herein eliminate other problems, such as ion beam shadowing, non-uniform thermal environments, and so on.

[0011] Specifically, according to embodiments of the present disclosure, a donor substrate of crystalline material is provided having a front surface and a back surface, and a support substrate is provided such that the back surface of the donor substrate can be bonded to the support substrate. As such, an ion dosage may be implanted to the front surface of the donor substrate to form a cleave plane within the donor substrate, thereby forming an implanted composite material. Consequently, a crystalline lamina may be cleaved from the donor substrate along the cleave plane, while the back surface remains bonded to the support substrate. Further features, embodiments, and implementation details are described in further detail herein.

[0012] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are intended to provide further explanation of the present invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The foregoing and other objects, features, aspects and advantages of the embodiments disclosed herein will become more apparent from the following detailed description when taken in conjunction with the following accompanying drawings.

[0014] FIG. 1 illustrates a general ion implantation followed by exfoliation.

[0015] FIG. 2 illustrates a more detailed ion implantation and exfoliation process.

[0016] FIG. 3 illustrates an example of donor wafer thickness over repeated use.

[0017] FIGS. 4A-4B illustrate an example issue of donor wafer bowing.

[0018] FIGS. 5A-5B illustrate example issues of handling a donor wafer.

[0019] FIG. 6 illustrates an example of supporting a crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina according to embodiments of the present invention.

[0020] FIGS. 7A-7B illustrate example benefits of for supporting a crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina according to embodiments of the present invention.

[0021] FIGS. 8A-8C illustrate example alternative bonding techniques for supporting a crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina according to embodiments of the present invention.

[0022] FIG. 9 illustrates an example procedure for supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina according to embodiments of the present invention.

[0023] It should be understood that the above-referenced drawings are not necessarily to scale, presenting a somewhat simplified representation of various preferred features illustrative of the basic principles of the disclosure. The specific design features of the present disclosure, including, for example, specific dimensions, orientations, locations, and shapes, will be determined in part by the particular intended application and use environment.

DETAILED DESCRIPTION OF THE INVENTION

[0024] The present invention relates to supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina.

[0025] According to the present invention, a method and process are described for addressing the above mentioned problems when cleaving a crystalline lamina from a crystalline donor material, such as the minimum thickness, bowing, handling, cooling, chipping, etc. In particular, with reference generally to FIG. 6, the techniques herein provide a support substrate (e.g., wafer) 80 that may be bonded to the provided donor substrate (e.g., wafer) 20. The donor substrate can be any material, including, for example, sapphire, silicon, silicon carbide, gallium nitride, gallium arsenide, aluminum nitride, diamond, or germanium, and can be a material of any practical thickness (such as from about 100 microns to about 10 mm) as well as any size and shape, including square, rectangular, or round, depending on the desired size and shape of the resulting crystalline lamina. Preferably, the donor substrate comprises sapphire.

[0026] The support substrate (wafer) 80 may advantageously be a low-cost multi-crystalline form of the crystalline donor material, and preferably is matched to have a substantially similar coefficient of thermal expansion to the donor. As example, the support substrate may be any suitable material, such as silicon carbide ceramic, alumina ceramic, aluminum nitride ceramic, glass, and fused silica. The low-cost support wafer thickness may be selected to be sufficiently large to reduce bowing of the donor substrate due to the cleaving, that is, that there is minimal bowing even when the donor becomes very thin. An example range of thickness is 1-8 mm, but other thicknesses are contemplated herein, and this example is not meant to limit the scope of the invention.

[0027] By bonding the “back” surface of the costly donor wafer to a lower-cost support wafer, the combined assembly (composite material) is more rigid and is better able to resist bowing due to implant stress on the “front” of the donor wafer. In particular, as shown in FIG. 6, an exfoliation process may include providing a donor substrate 20 and support substrate 80, where the surfaces of the donor substrate 20 and support substrate 80 may be processed (e.g., polished, annealed, etched, etc.) in order to remove any residual damage or impurities. Any bonding technique may be used to bond the donor and support together, temporarily or permanently, in order to form a bonded composite, including the use of various adhesives for bonding the lamina to the backing substrate, such as, for example, glass frit, polymer adhesives, anodic bonding, and, preferably, atomic (fusion) bonding.

[0028] The process may further include implanting an ion dosage 10 into the donor substrate 20 to (e.g., through) the front surface of the donor substrate to form a cleave plane within the donor substrate beneath the surface. The ion dosage 10 may comprise, for example, hydrogen ions, helium ions, or both. Specifically, as a result of the implantation (thus forming an implanted composite material), an implant layer 30, which is formed due to stress caused by the ion implantation (e.g., implantation stress), may form in the donor substrate 20 under the surface through which the ions 10 are implanted. The implant layer 30 may cause a compressive stress within the donor substrate 20. This is because the implant layer 30 naturally attempts to expand within the donor substrate 20, but it is restrained by the thicker crystalline material which comprises the substrate 20. Notably, the implant layer 30 coincides with the cleave plane, from which the lamina 40 eventually separates from the donor substrate 20. Overall implantation conditions can be varied as needed to produce the desired cleave plane at a depth required to provide a crystalline lamina of the desired thickness. For example, the total implant dosage may be any dosage between about 1.0×10^{14} and 1.0×10^{18} H/cm², such as $0.5 - 3.0 \times 10^{17}$ H/cm². The total dosage energy can also be varied, such as greater than or equal to about 50 keV, including between about 500 keV to about 3 MeV. In some embodiments, the ion implantation temperature may be maintained between about 200°C and 950°C, such as between 300°C and 800°C or between 550°C and 750°C, and this can be adjusted depending upon the specific type of donor body. For example, when the donor substrate is sapphire, the ion implantation temperature may be between 500°C and 800°C.

[0029] In one embodiment, such as for thin crystalline lamina (e.g., lamina having a thickness of less than 50 microns), it may be desirable to bond a backing or “handle” substrate 50, such as glass or plastic, to the implanted donor body prior to exfoliation, in order to improve handling of the resulting lamina. Any bonding technique may be used to bond the donor 20 and the handle 50 together, temporarily or permanently, in order to form a bonded composite, including the use of various adhesives for bonding the lamina to the backing substrate, such as, for example, glass frit, polymer adhesives, anodic bonding, and atomic (fusion) bonding. Notably, a temporary bond may be created with the donor substrate (at the portion that will become lamina 40) before the cleaving, thereby forming a composite structure. When cleaving

(exfoliating) the lamina from the donor substrate in this optional embodiment (described below), both the lamina 40 and the handle substrate 50 are cleaved from the donor substrate 20. The handle substrate may be used to optionally further process the cleaved lamina, such as to polish the cleaved surface or to apply additional coatings or layers to the lamina, and may be removed to produce a free-standing lamina. Alternatively, the handle substrate 50 may be permanently attached, which may be advantageous for various applications of the cleaved lamina 40. For example, the handle substrate may be a transparent material, such as glass, which remains permanently bonded to the exfoliated lamina 40, and the resulting multilayer composite may be used as a screen for an electronic device. Non-transparent substrates may be useful in applications such as adding a protective layer to decorative glass or plastic.

[0030] As shown in FIG. 6, the exfoliation process may further include cleaving, or exfoliating, crystalline lamina 40 from the donor substrate 20 along the cleave plane, while the back surface remains bonded to the support substrate. The lamina 40 is a thin sheet of the crystalline material which makes up the donor substrate 20. The donor substrate 20 may be heated (for example), causing the material above the implant layer 30 to cleave off or exfoliate, thus forming the lamina 40. The lamina 40 is cleaved from the donor substrate 10 along the cleave plane defined by the implanted ion dosage. Notably, any method known in the art can be used to cleave or exfoliate the lamina, including thermal cleaving or mechanical cleaving, and specific cleaving conditions, such as exfoliation temperature, heating rate, exposure time, and exfoliation pressure, can be varied depending, for example, on the lamina thickness as well as on the implant conditions used. For example, the crystalline lamina of sapphire having a thickness of less than 100 microns, such as less than 50 microns, less than 30 microns, less than 25 microns, and less than 15 microns, can be thermally exfoliated from the donor body using temperatures from about 400°C to about 1200°C, such as from about 600°C to about 1000°C, and for a time between about 1 minute to about 60 minutes, such as from about 5 minutes to about 30 minutes. Higher exfoliation temperatures would generally require less time. In addition, a thermal temperature ramp up can be used in order to shorten the amount of time spent at the exfoliation temperature. By adjusting implantation and exfoliation conditions, the area of the resulting lamina that is substantially free of physical defects can be maximized. Optionally, the

donor body may undergo thermal treatment prior to exfoliation. For example, the donor body may be heated below the exfoliation temperature in order to cause damage evolution in the cleave layer, such as by Oswalt ripening. Heat treatment may reduce the time and temperature needed for exfoliation of a full lamina and may produce a smoother cleave surface. An additional or alternative short duration thermal treatment can also be optionally used after exfoliation to anneal the crystalline lamina if desired in order remove or reduce any damage potentially caused by implantation.

[0031] The exfoliation process may further include polishing and annealing the donor substrate surface, through which the ion dosage 10 was implanted, in order to prepare the donor substrate 20 for a subsequent exfoliation cycle. That is, the surface of the donor substrate 20 may be processed (e.g., polished, annealed, etched, etc.) in order to remove any residual damage or impurities from the previous exfoliation cycle. The donor substrate 20 may be reused in this manner (e.g., polished, implanted, exfoliated, polished again, and so forth) for multiple exfoliation cycles, while still bonded to the support substrate 80. Said differently, the cleaving creates an exposed surface on the donor substrate, and additional ion dosages may be implanted through the exposed surface of the donor substrate to form additional cleave planes within the donor substrate (forming additional implanted composite materials). As such, additional crystalline lamina may be cleaved from the donor substrate along these newly created (additional) cleave planes, while the back surface remains bonded to the support substrate.

[0032] As shown in FIG. 7A, the cleaving of additional lamina may continue until reaching the back surface of the donor substrate 20 (i.e., reaching or nearly reaching the support substrate 80). In this manner, the support substrate need only be bonded once per donor body 20, so the cost of this bonding step can thus be divided among all the lamina slices of the donor, making the marginal cost per slice relatively low. That is, the donor wafer may be sliced to a minimum thickness of zero (or nearly zero) since it remains well supported throughout. This dramatically reduces the amount of donor material wasted and allows nearly 100% material utilization. The support substrate wafer can be re-polished and reused once the donor has been fully sliced, i.e., removing residual donor material from the support substrate after reaching the

back surface of the donor substrate, and another donor substrate can be bonded to the previously used support substrate.

[0033] Notably, the donor substrate 20 and support substrate 80 may have different dimensions and/or shapes. For instance, the support substrate 80 may be larger in diameter (for circular wafers) or a completely different shape than the donor wafer. As shown in FIG. 7B, this allows automated handling equipment 60 to process the assembly without risk to the critically important edges of the donor 20. Supporting the donor from the support substrate 80 in this way, i.e., handling only the support substrate during one or both of the cleaving and implanting, also prevents mechanical holders 60 from shadowing the ion beam during the implanting or causing temperature non-uniformities in the donor substrate near the points of contact with the holder (during one or both of the cleaving and implanting). Notably, the support substrate can also enhance the radiative cooling of the donor due to a higher emissivity of the support, thereby allowing processing at lower temperatures or higher beam currents (throughputs) with a given machine configuration.

[0034] Additionally, as shown in FIGS. 8A-8C, bonding the (back) surface of the donor substrate 20 to the support substrate 80 may comprises bonding the entire surface of the donor substrate to the support substrate, or else only select portions of the back surface of the donor substrate to the support substrate. For example, as shown in FIG. 8A, the entire back surface of the donor substrate 20 is bonded to the support substrate 80 (note that not the entire surface of the support substrate is bonded, since it is a larger dimension). Alternatively, as shown in FIG. 8B, the shape of the support substrate 80 may be designed to allow for only portions to be bonded to the donor substrate 20, such as various “pins” 80P. Note that any number and location of such portions (e.g., pins) may be used, and the view shown in FIG. 8B is merely for example. Alternatively still, in FIG. 8C, a “picture frame” shaped substrate (e.g., rectangular, circular, etc.) may bond to only the outer portions of the donor substrate back surface. Such alternative configurations may be used to reduce the required bonding surface area, and may be useful for temperature control, ion implantation techniques, and so on. (Note further, that, although not preferred, the support substrate 80 may also overlap (i.e., drape over) the sides of the donor substrate 20, whether bonded to the sides or not, in any configuration of FIGS. 8A-8C above.)

[0035] FIG. 9 illustrates an example simplified procedure for cleaving a crystalline lamina from a crystalline donor material. As shown in FIG. 9, the procedure 900 may start at step 905, continue to step 910, and so forth. Although FIG. 9 depicts steps in a particular order, it should be understood that the depicted embodiment is not limiting, and the particular order is depicted merely for illustration purposes.

[0036] At step 910, a support substrate is provided (e.g., with a thickness of the support substrate selected to reduce bowing of the donor substrate due to the cleaving, as mentioned above), and in step 915 a donor substrate of crystalline material is also provided having a front surface and a back surface. As detailed herein, in step 920 the back surface of the donor substrate is bonded (e.g., fusion bonded) to the support substrate. For instance, the bonding may be across the complete back surface, or else only on select portions of the back surface.

[0037] While handling only the support substrate, in step 925 an ion dosage may be implanted to the front surface of the donor substrate to form a cleave plane within the donor substrate, thereby forming an implanted composite material, and in step 935 a crystalline lamina may then be cleaved from the donor substrate along the cleave plane, while the back surface remains bonded to the support substrate. Optionally, in one embodiment, in step 930 the front surface of the donor substrate may also be bonded to a handle substrate to form a supported composite material prior to cleaving the crystalline lamina (e.g., and while the handle remains bonded to the cleaved crystalline lamina).

[0038] As described above, an additional (e.g., second) ion dosage may be implanted in step 940 through the exposed surface of the donor substrate to form an additional (e.g., second) cleave plane within the donor substrate, thereby forming a second implanted composite material, such that in step 945 an additional crystalline lamina may be cleaved from the donor substrate along the additional (e.g., second) cleave plane, while the back surface remains bonded to the support substrate. Note that additional handle substrates may also be bonded to the exposed surfaces (such as in step 930) prior to the cleaving in step 945. Steps 940 and 945 may be repeated to implant additional ion dosages and cleave further additional crystalline laminae (e.g., and handle substrates) from the donor substrate, while the back surface remains bonded to the support substrate, until reaching the back surface of the donor substrate in step 950.

[0039] At this time, in step 955, residual donor material may be removed from the support substrate after reaching the back surface of the donor substrate (e.g., polishing the support substrate), and the process 900 may repeat to bond an additional back surface of an additional donor substrate (e.g., provided in step 915) to the now cleaned (e.g., polished) support substrate. The process 900 may continue to repeat with the same support substrate until a new substrate is needed, or until no further lamina are desired.

[0040] It should be understood that the steps shown in FIG. 9 are merely examples for illustration, and certain steps may be included or excluded as desired. Further, while a particular order of the steps is shown, this ordering is merely illustrative, and any suitable arrangement of the steps may be utilized without departing from the scope of the embodiments herein.

[0041] The components, arrangements, and techniques described herein, therefore, provide for supporting crystalline donor material when it is subjected to ion implantation and exfoliation to produce a crystalline lamina. In particular, the techniques described herein prevent bowing of the donor material, thereby allowing high-quality fusion bonding to the handle substrate. In addition, nearly 100% utilization of donor material (which may be relatively expensive) may be achieved, reducing waste and manufacturing costs, with easier and more reliable automated handling of the expensive donor material (e.g., minimizing the risk of damaging or chipping critical edges). Moreover, the techniques herein eliminate the problem of ion beam shadowing during implantation, and may provide for a more uniform thermal environment during cleaving.

[0042] Notably, the present disclosure further relates to a thin, crystalline lamina (or film), as manufactured using the techniques described herein, or also to a composite material formed by adhering a crystalline lamina to a handle substrate, such as glass or plastic. Such a lamina or composite material may be transparent and used for screens (cover glasses) for consumer goods, such as watches, mobile phones, and other various electronics, as well as for other purposes.

[0043] In one specific embodiment, the disclosed embodiments may be used to prepare a cover plate of an electronic device. For example, there are many types of mobile electronic devices currently available which include a display window assembly that is at least partially transparent. These include, for example, handheld electronic devices such media players, mobile

telephones (cell phones), personal data assistants (PDAs), pagers, and laptop computers and notebooks. The display screen assembly may include multiple component layers, such as, for example, a visual display layer such as a liquid crystal display (LCD), a touch sensitive layer for user input, and at least one outer cover layer used to protect the visual display. Each of these layers are typically laminated or bonded together.

[0044] Many of the mobile electronic devices used today are subjected to excessive mechanical and/or chemical damage, particularly from careless handling and/or dropping, from contact of the screen with items such as keys in a user's pocket or purse, or from frequent touch screen usage. For example, the touch screen surface and interfaces of smartphones and PDAs can become damaged by abrasions that scratch and pit the physical user interface, and these imperfections can act as stress concentration sites making the screen and/or underlying components more susceptible to fracture in the event of mechanical or other shock. Additionally, oil from the user's skin or other debris can coat the surface and may further facilitate the degradation of the device. Such abrasion and chemical action can cause a reduction in the visual clarity of the underlying electronic display components, thus potentially impeding the use and enjoyment of the device and limiting its lifetime.

[0045] Accordingly, a composite material described herein may comprise a plastic or glass handle or backing substrate (e.g., transparent) bonded to a thin lamina (e.g., also transparent) of a hard crystalline material (e.g., sapphire) having a thickness of less than 100 microns, such as less than 100 microns, less than 50 microns, less than 30 microns, less than 25 microns, and less than 15 microns. The lamina may be particularly produced using the implantation and cleaving method described above.

[0046] The foregoing description of preferred embodiments of the present disclosure has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the embodiments to the precise form disclosed. Modifications and variations are possible in light of the above teachings, or may be acquired from practice of the disclosed embodiments. For example, a method for use with exfoliating a lamina from a crystalline material is contemplated, as well as a system for use with exfoliating a lamina from a crystalline material and a crystalline lamina. The embodiments were chosen and described in order to

explain the principles of the invention and its practical application to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.

CLAIMS

What is claimed is:

1. A method for cleaving a crystalline lamina from a crystalline donor material, the method comprising:

providing a donor substrate of crystalline material having a front surface and a back surface;

providing a support substrate;

bonding the back surface of the donor substrate to the support substrate;

implanting an ion dosage to the front surface of the donor substrate to form a cleave plane within the donor substrate, thereby forming an implanted composite material; and

cleaving a crystalline lamina from the donor substrate along the cleave plane, while the back surface remains bonded to the support substrate.

2. The method as in claim 1, wherein the cleaving creates an exposed surface on the donor substrate, the method further comprising:

implanting a second ion dosage through the exposed surface of the donor substrate to form a second cleave plane within the donor substrate, thereby forming a second implanted composite material; and

cleaving an additional crystalline lamina from the donor substrate along the second cleave plane, while the back surface remains bonded to the support substrate.

3. The method as in claim 2, further comprising:

implanting additional ion dosages and cleaving further additional crystalline laminas from the donor substrate, while the back surface remains bonded to the support substrate, until reaching the back surface of the donor substrate.

4. The method as in claim 3, further comprising:

removing residual donor material from the support substrate after reaching the back surface of the donor substrate; and

bonding a second back surface of a second donor substrate to the support substrate.

5. The method as in claim 1, wherein the ion dosage comprises hydrogen ions, helium ions, or both.

6. The method as in claim 1, further comprising:

bonding the front surface of the donor substrate to a handle substrate prior to cleaving the crystalline lamina, thereby forming a supported composite material.

7. The method as in claim 1, further comprising:

selecting a thickness of the support substrate to reduce bowing of the donor substrate due to the cleaving.

8. The method as in claim 1, wherein the donor substrate and support substrate have different dimensions.

9. The method as in claim 1, wherein the donor substrate and support substrate have different shapes.

10. The method as in claim 1, wherein bonding the back surface of the donor substrate to the support substrate comprises:

bonding only select portions of the back surface of the donor substrate to the support substrate.

11. The method as in claim 1, wherein the donor substrate and support substrate have substantially similar coefficients of thermal expansion.

12. The method as in claim 1, wherein the support substrate is a multi-crystalline form of the crystalline material of the donor substrate.

13. The method as in claim 1, further comprising:

handling only the support substrate during one or both of the cleaving and implanting.

14. The method as in claim 13, wherein the handling comprises:

preventing ion beam shadowing during the implanting.

15. The method as in claim 13, wherein the handling comprises:

preventing temperature non-uniformities in the donor substrate during one or both of the cleaving and implanting.

16. The method as in claim 1, wherein bonding comprises fusion bonding.

17. The method as in claim 1, wherein the crystalline material is selected from a group consisting of: sapphire, silicon, silicon carbide, gallium nitride, gallium arsenide, aluminum nitride, diamond, and germanium.

18. The method as in claim 1, wherein the support substrate is selected from a group consisting of: silicon carbide ceramic, alumina ceramic, aluminum nitride ceramic, glass, and fused silica.

19. A system for cleaving a crystalline lamina from a crystalline donor material, the system comprising:

a bonding apparatus configured to a) receive a donor substrate of crystalline material having a front surface and a back surface; b) receive a support substrate; and c) bond the back surface of the donor substrate to the support substrate;

an ion beam implanter configured to implant an ion dosage to the front surface of the donor substrate to form a cleave plane within the donor substrate, thereby forming an implanted composite material; and

a cleaving apparatus configured to cleave a crystalline lamina from the donor substrate along the cleave plane, while the back surface remains bonded to the support substrate.

20. The system as in claim 19, wherein the cleaving apparatus creates an exposed surface on the donor substrate when cleaving, the implanter further configured to implant a second ion dosage through the exposed surface of the donor substrate to form a second cleave plane within the donor substrate, thereby forming a second implanted composite material, and the cleaving apparatus further configured to cleave an additional crystalline lamina from the donor substrate along the second cleave plane, while the back surface remains bonded to the support substrate.

21. The system as in claim 20, wherein the implanter is further configured to implant additional ion dosages and the cleaving apparatus is further configured to cleave further additional crystalline laminas from the donor substrate, while the back surface remains bonded to the support substrate, until reaching the back surface of the donor substrate.
22. The system as in claim 19, further comprising:
a substrate preparing apparatus configured to remove residual donor material from the support substrate after reaching the back surface of the donor substrate;
wherein the bonding apparatus is further configured to bond a second back surface of a second donor substrate to the support substrate.
23. The system as in claim 19, wherein the ion dosage comprises hydrogen ions, helium ions, or both.
24. The system as in claim 19, further comprising:
a second bonding apparatus configured to bond the front surface of the donor substrate to a handle substrate prior to the crystalline lamina being cleaved, thereby forming a supported composite material.
25. The system as in claim 19, wherein a thickness of the support substrate is selected to reduce bowing of the donor substrate due to the cleaving.
26. The system as in claim 19, wherein the donor substrate and support substrate have different dimensions.

27. The system as in claim 19, wherein the donor substrate and support substrate have different shapes.

28. The system as in claim 19, wherein only select portions of the back surface of the donor substrate are bonded to the support substrate.

29. The system as in claim 19, wherein the donor substrate and support substrate have substantially similar coefficients of thermal expansion.

30. The system as in claim 19, wherein the support substrate is a multi-crystalline form of the crystalline material of the donor substrate.

31. The system as in claim 19, further comprising:

a handling mechanism configured to handle only the support substrate during the cleaving.

32. The system as in claim 31, wherein the handling mechanism is configured to prevent ion beam shadowing during the cleaving.

33. The system as in claim 31, wherein the handling mechanism is configured to prevent temperature non-uniformities in the donor substrate during the cleaving.

34. The system as in claim 19, wherein the bonding apparatus comprises a fusion bonding apparatus.

35. The system as in claim 19, wherein the crystalline material is selected from a group consisting of: sapphire, silicon, silicon carbide, gallium nitride, gallium arsenide, aluminum nitride, diamond, and germanium.

36. The system as in claim 19, wherein the support substrate is selected from a group consisting of: silicon carbide ceramic, alumina ceramic, aluminum nitride ceramic, glass, and fused silica.

37. A composite material for use with cleaving a crystalline lamina from a crystalline donor material, the composite material comprising:

a donor substrate of crystalline material having a front surface and a back surface; and

a support substrate bonded to the back surface of the donor substrate;

wherein the donor substrate further comprises a cleave plane within the donor substrate below the front surface.

38. The composite material as in claim 37, further comprising:

a handle substrate bonded to the front surface of the donor substrate, thereby forming a supported composite material.

39. The composite material as in claim 37, wherein only select portions of the back surface of the donor substrate are bonded to the support substrate.

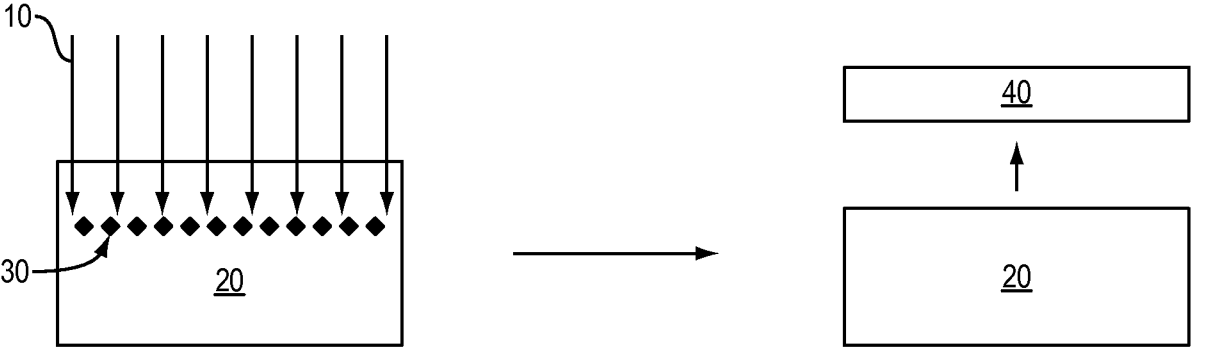
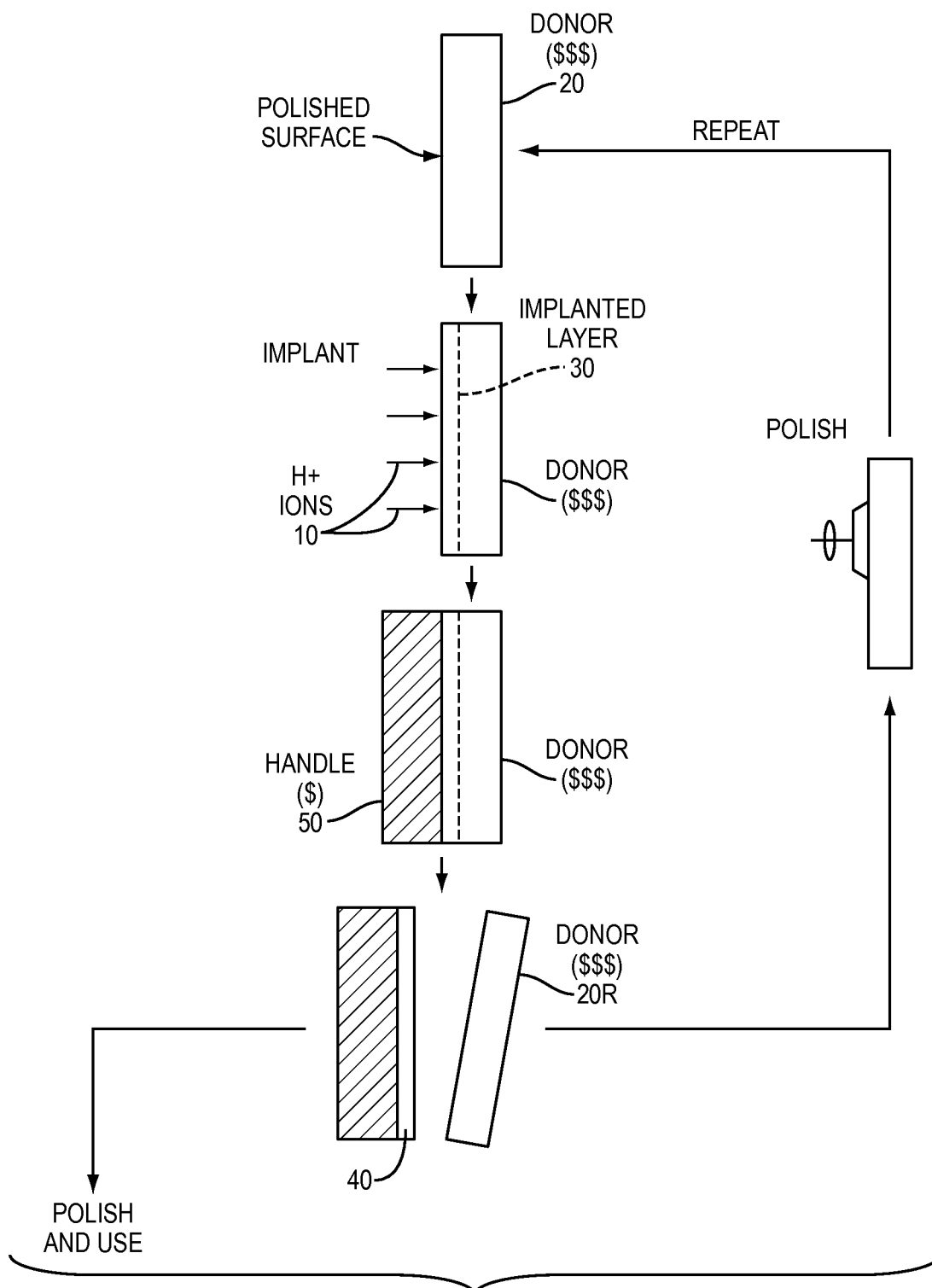


FIG. 1



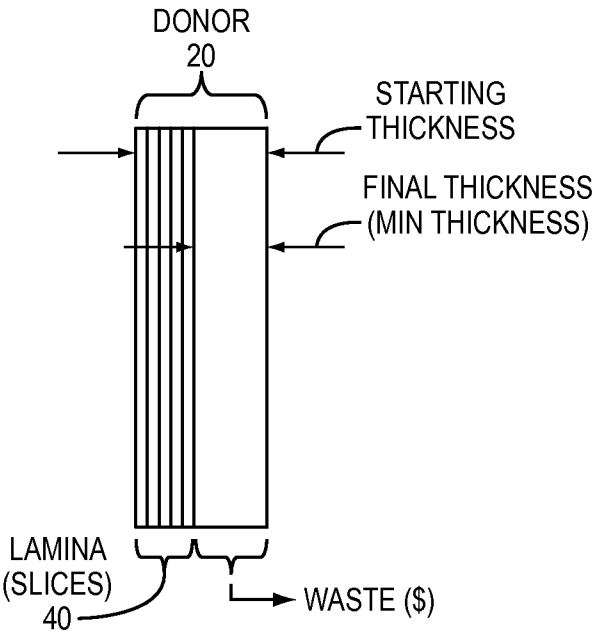


FIG. 3

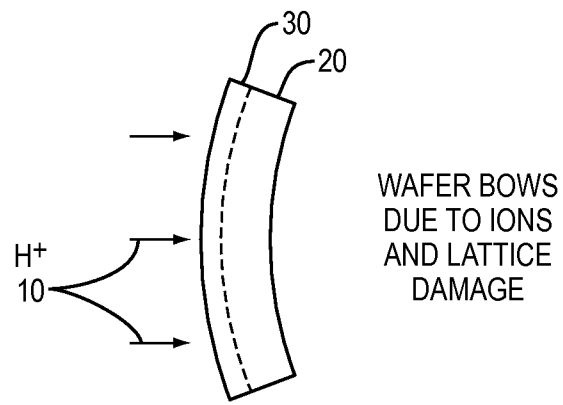


FIG. 4A

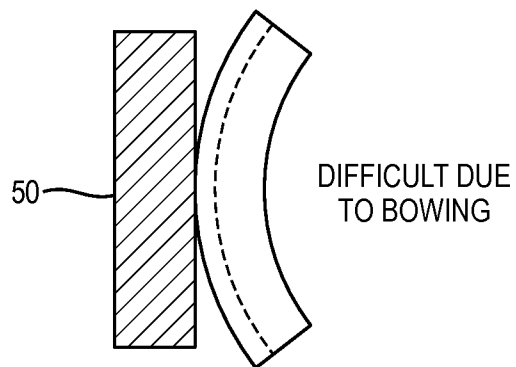


FIG. 4B

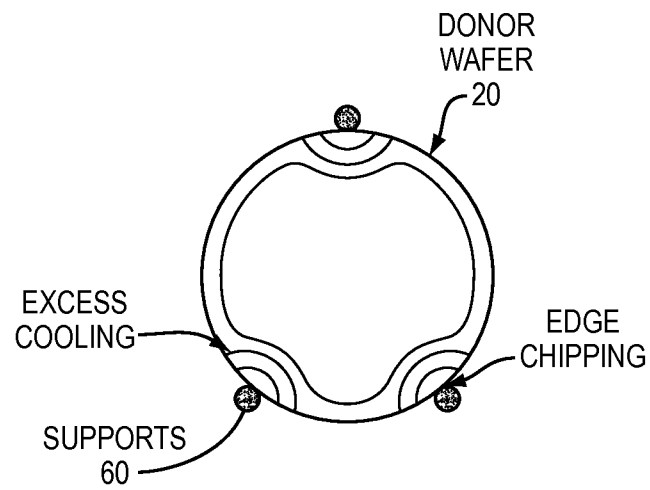


FIG. 5A

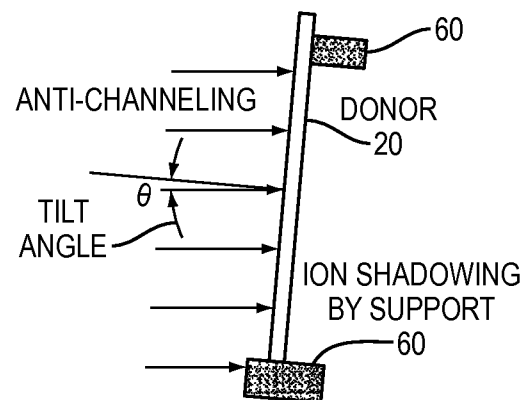
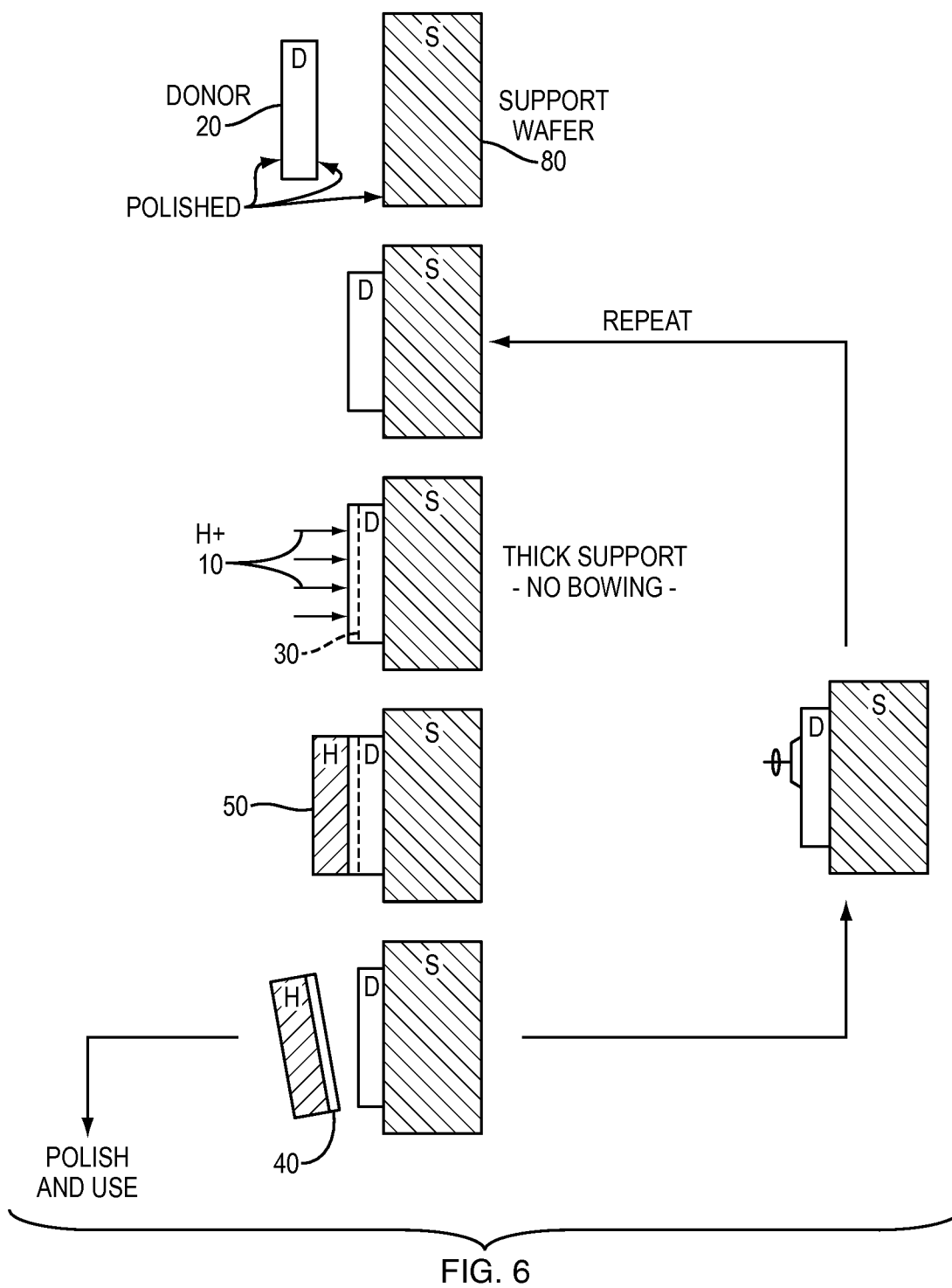


FIG. 5B



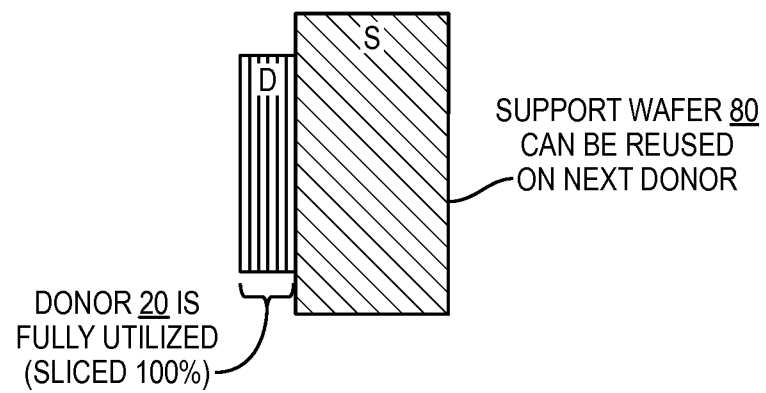


FIG. 7A

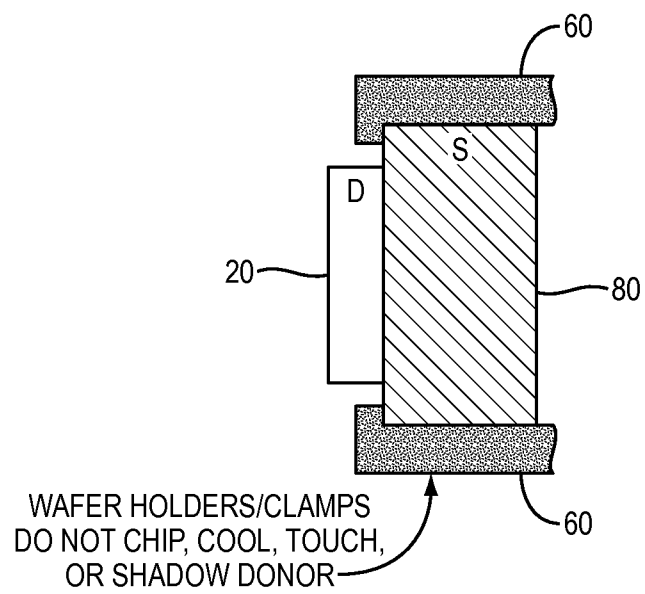


FIG. 7B

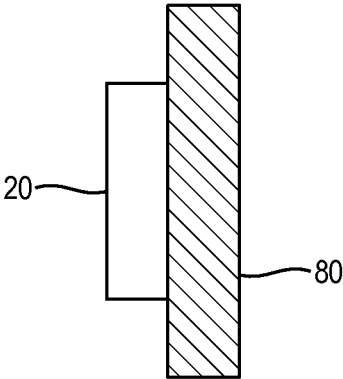


FIG. 8A

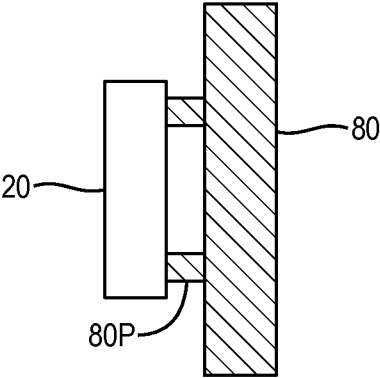


FIG. 8B

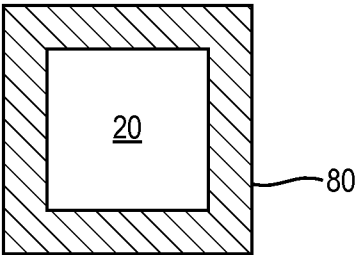


FIG. 8C

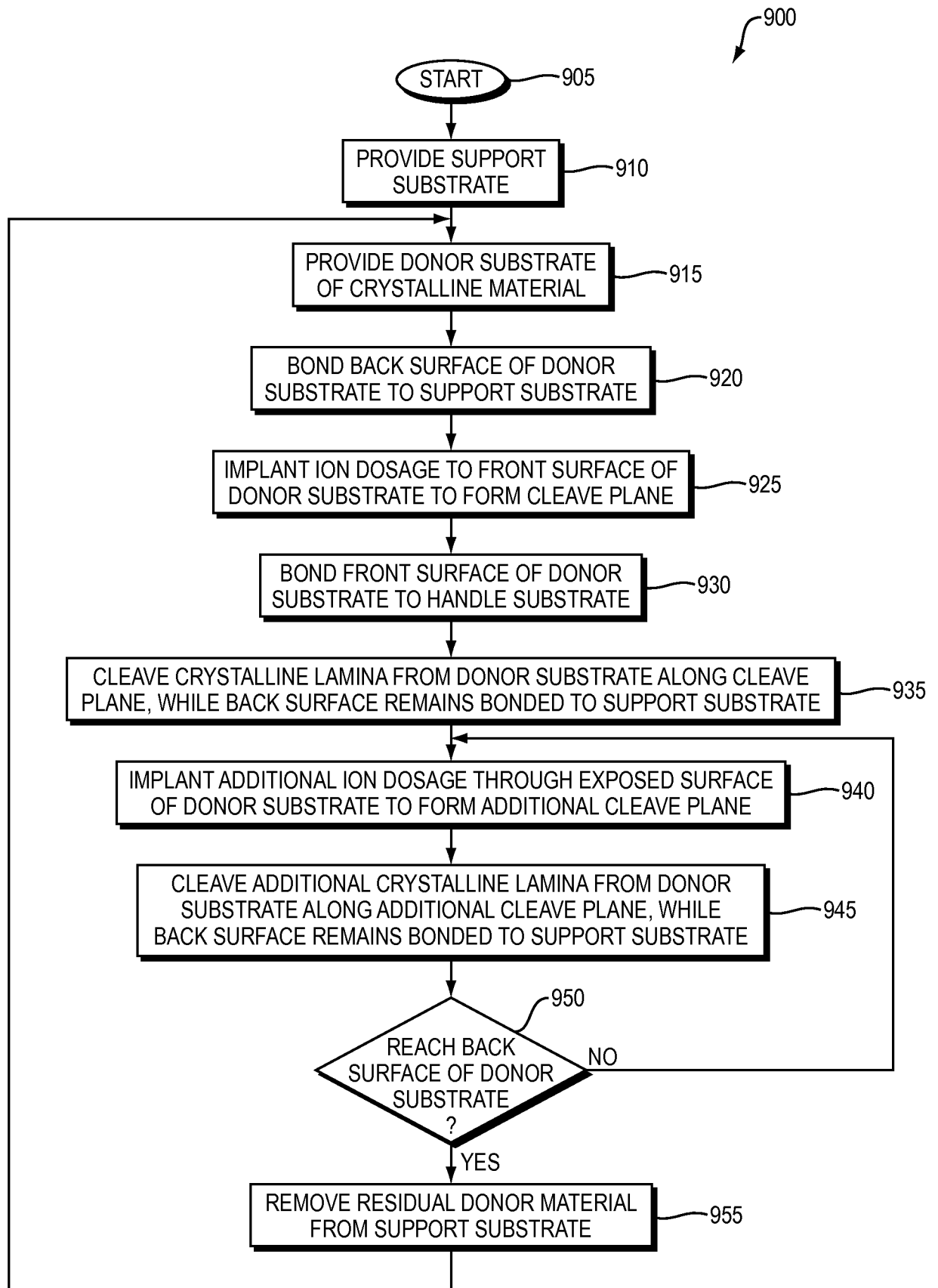


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/039485**A. CLASSIFICATION OF SUBJECT MATTER****H01L 21/265(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L 21/265; H01L 21/302; H01L 21/46; B32B 38/10; H01L 21/30; H01L 29/06; H01L 21/461

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & keywords: ion, implant, donor, support, cleave

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012-0168091 A1 (ADAM KELL et al.) 05 July 2012 See abstract, paragraphs [0017]-[0036] and figures 1-3, 5A-5B.	1-39
Y	US 2002-0081822 A1 (KAZUTAKA YANAGITA et al.) 27 June 2002 See abstract, paragraphs [0118]-[0160] and figures 1A-1G.	1-39
Y	US 2004-0214434 A1 (HARRY A. ATWATER JR. et al.) 28 October 2004 See abstract, paragraphs [0053], [0133] and figure 14.	7, 15, 25, 33
A	US 2010-0096733 A1 (ERIC GUIOT et al.) 22 April 2010 See abstract, paragraphs [0044]-[0072] and figure 1.	1-39
A	US 2001-0003668 A1 (KAZUTAKA YANAGITA et al.) 14 June 2001 See abstract, paragraphs [0050]-[0057] and figures 1A-1C.	1-39



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

21 October 2015 (21.10.2015)

Date of mailing of the international search report

21 October 2015 (21.10.2015)

Name and mailing address of the ISA/KR

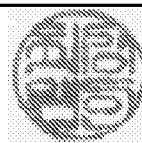
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/039485

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