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(54) **WAFER BONDED VIRTUAL SUBSTRATE AND METHOD FOR FORMING THE SAME**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 294 days.

This patent is subject to a terminal disclaimer.

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US 2004/0214434 A1 Oct. 28, 2004

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(63) Continuation-in-part of application No. 10/125,133, filed on Apr. 17, 2002, now Pat. No. 7,019,339.

(60) Provisional application No. 60/526,332, filed on Dec. 2, 2003, provisional application No. 60/284,726, filed on Apr. 17, 2001.

(51) **Int. Cl.**
H01L 21/302 (2006.01)
H01L 21/461 (2006.01)

(52) **U.S. Cl.** **438/752**; 438/933; 257/183; 257/184; 257/200

(58) **Field of Classification Search** .... None
See application file for complete search history.

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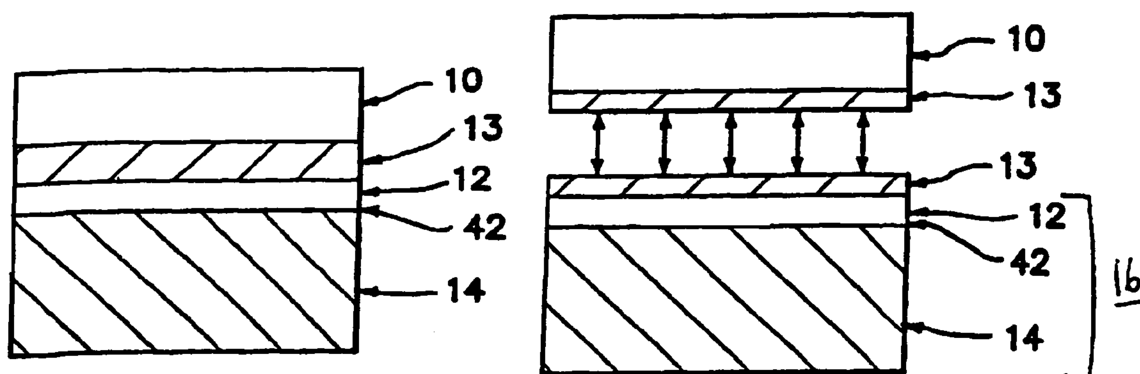
(57) **ABSTRACT**

A method of forming a virtual substrate comprised of an optoelectronic device substrate and handle substrate comprises the steps of initiating bonding of the device substrate to the handle substrate, improving or increasing the mechanical strength of the device and handle substrates, and thinning the device substrate to leave a single-crystal film on the virtual substrate such as by exfoliation of a device film from the device substrate. The handle substrate is typically Si or other inexpensive common substrate material, while the optoelectronic device substrate is formed of more expensive and specialized electro-optic material. Using the methodology of the invention a wide variety of thin film electro-optic materials of high quality can be bonded to inexpensive substrates which serve as the mechanical support for an optoelectronic device layer fabricated in the thin film electro-optic material.

22 Claims, 7 Drawing Sheets



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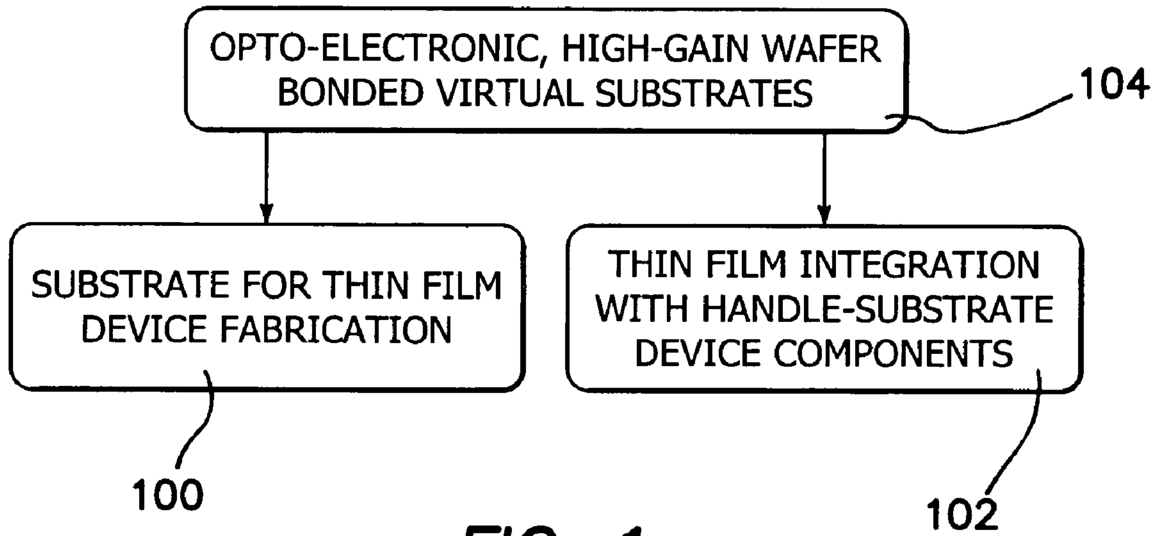

FIG. 1

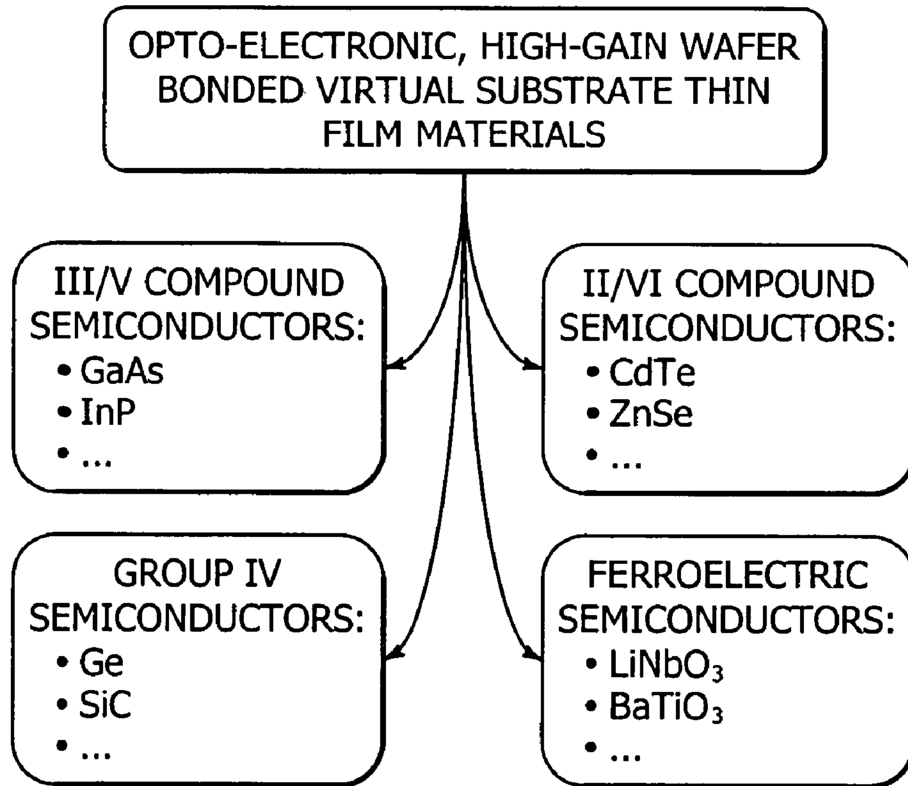

FIG. 2

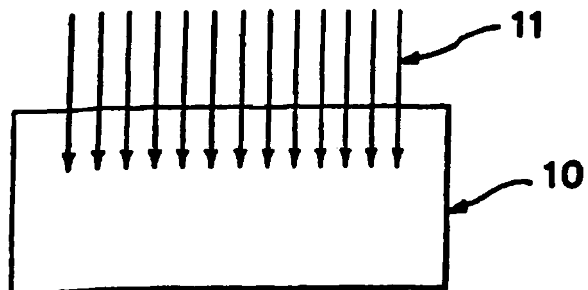

FIG. 3A

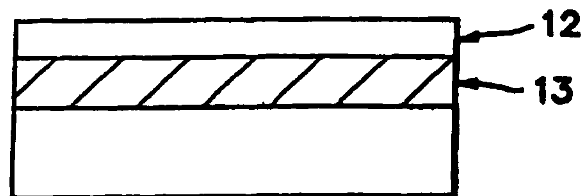

FIG. 3B

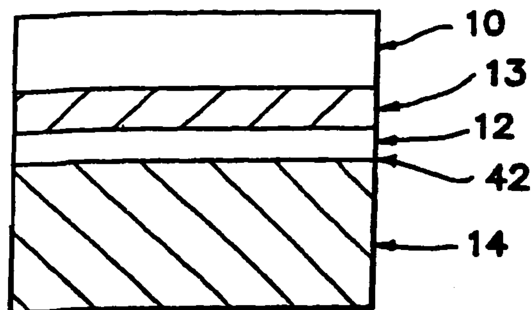

FIG. 4A

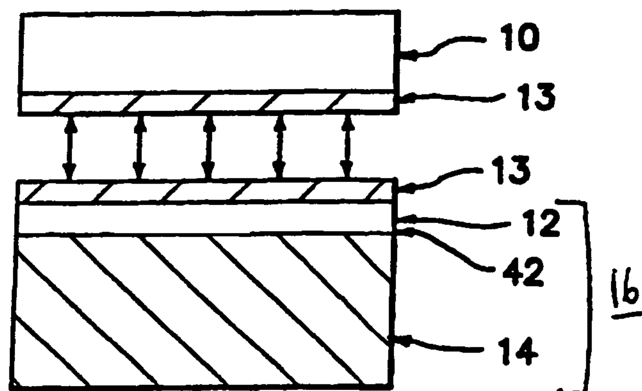

FIG. 4B

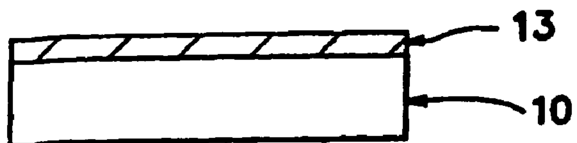

FIG. 5A

FIG. 5B

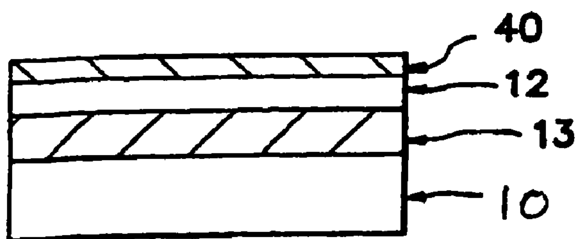

FIG. 6A

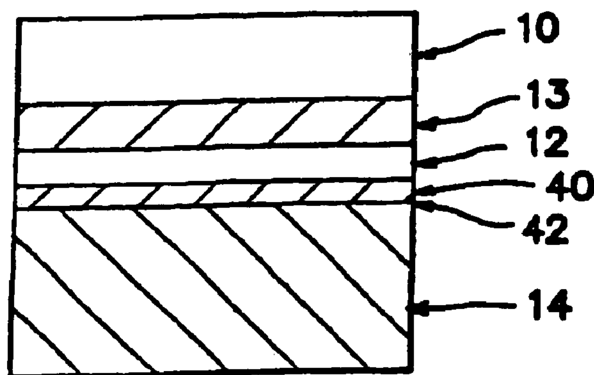

FIG. 6B

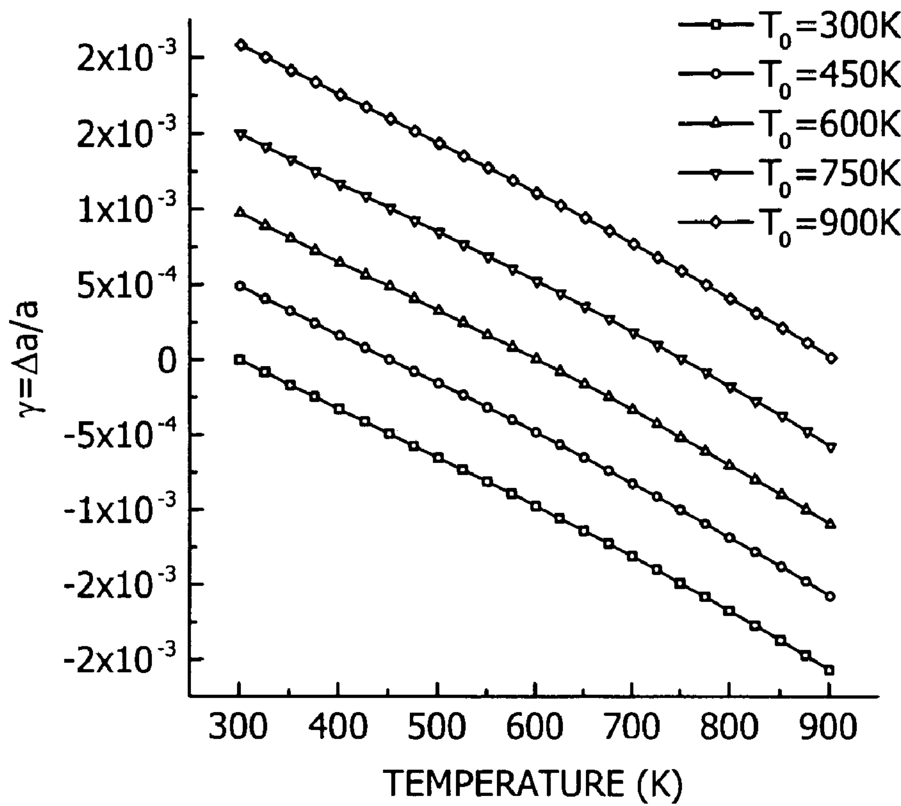

FIG. 7

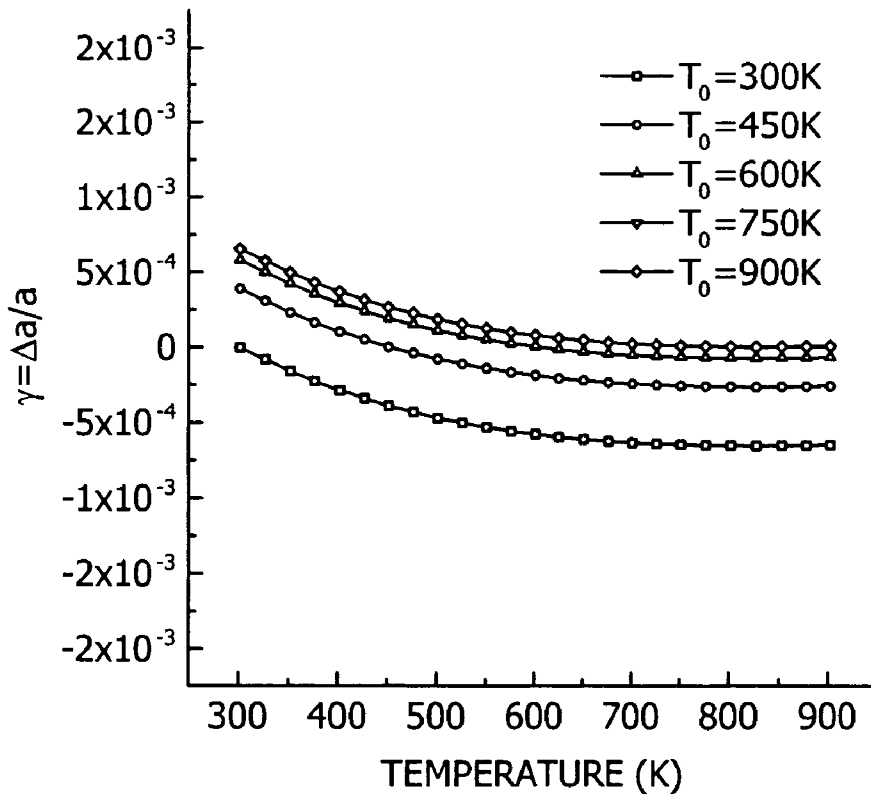

FIG. 8

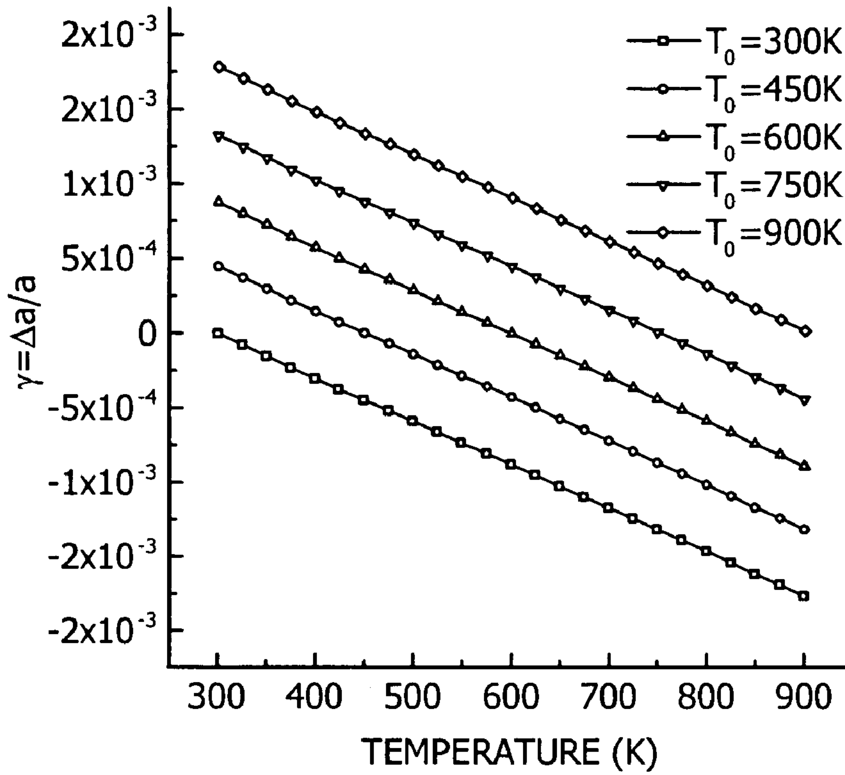

FIG. 9

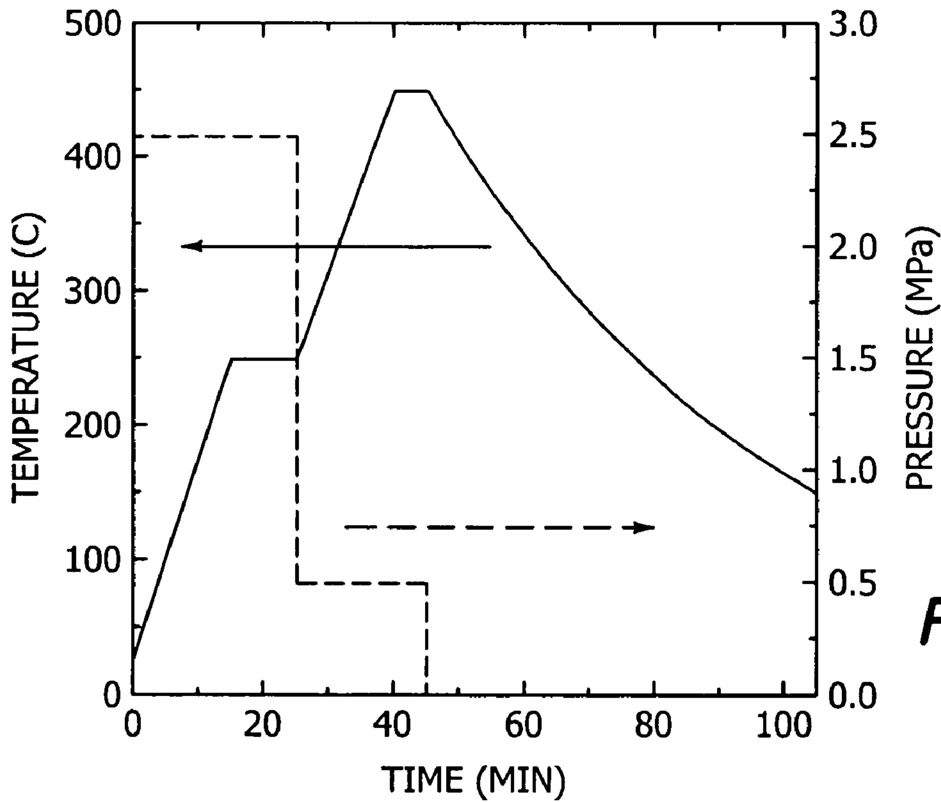

FIG. 10

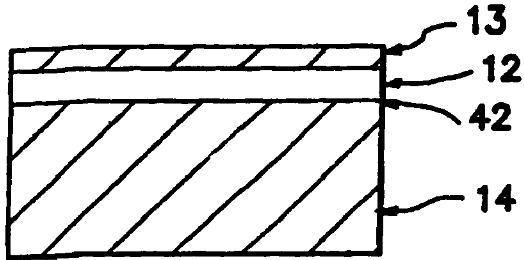

FIG. 11A

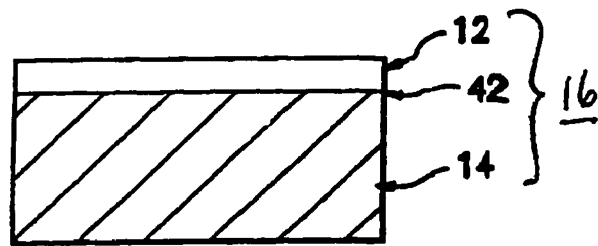

FIG. 11B

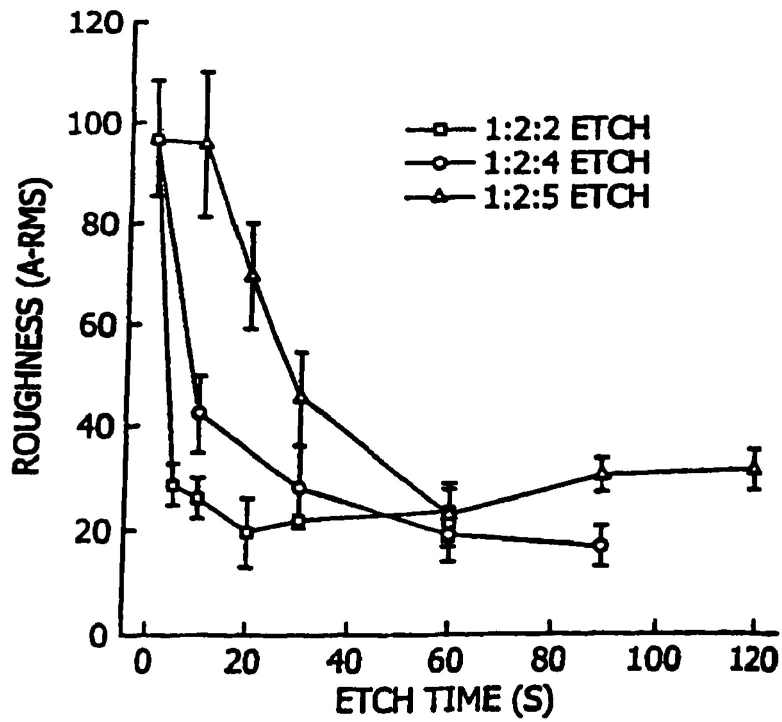

FIG. 12A

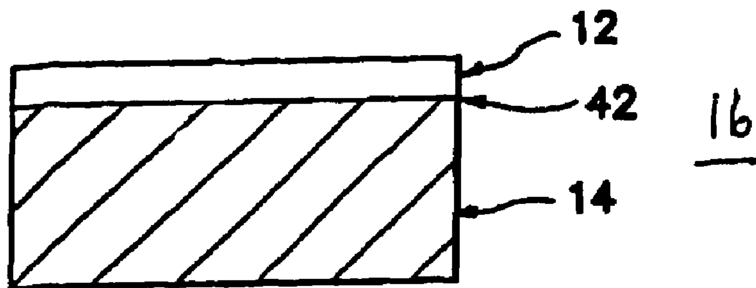

FIG. 13A

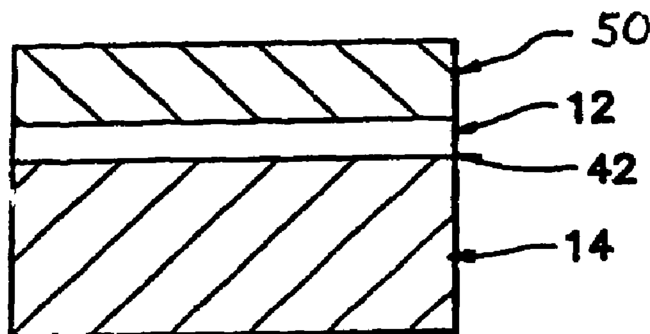

FIG. 13B

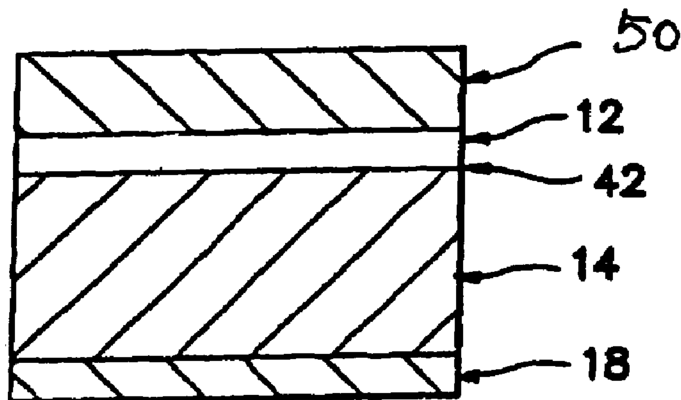

FIG. 14

WAFER BONDED VIRTUAL SUBSTRATE AND METHOD FOR FORMING THE SAME

RELATED APPLICATIONS

The present application is a continuation-in-part application related under 35 USC 120 to U.S. patent application Ser. No. 10/125,133 filed on Apr. 17, 2002 now U.S. Pat. No. 7,019,339, which is incorporated herein by reference, and which in turned claimed priority to U.S. Provisional Patent Application Ser. No. 60/284,726, filed on Apr. 17, 2001 which claimed priority pursuant to 35 USC 119, and to copending U.S. Provisional Patent Application Ser. No. 60/526,332, filed on Dec. 2, 2003, which is incorporated herein by reference, to which priority is claimed pursuant to 35 USC 119.

FEDERAL SUPPORT STATEMENT

This invention was made with government support under Contract No. DE-AC36-99G010337, Midwest Research Institute Subcontract No. ACQ-1-30619-13 awarded by the Department of Energy and Contract No. NAS3-02201, Subcontract No. 200492; LEW-17946-1 awarded by NASA. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to the field of semiconductor processing of films and in particular to processing nonsilicon films.

2. Description of the Prior Art

The optoelectronics, photovoltaics, telecommunications, and LED industries have a need for a substrate technology that allows them to use a low-cost readily available substrate like Si as a mechanical support for a thin film of optoelectronic material on which to fabricate a device. Some obvious advantages are improved mechanical strength and superior thermal conductivity relative to a bulk optoelectronic material.

Group III-V semiconductor layered structures grown on bulk germanium substrates have been used in the prior art to create high efficiency triple-junction solar cells with efficiencies greater than 30%. However, these are prohibitively expensive for all but space applications, because the Ge substrate constitutes a large portion of this cost.

The optoelectronics, photovoltaics, telecommunications, and LED industries would benefit from adopting a substrate technology that allows them to use a low-cost readily available substrate like Si as a mechanical support for a thin film of optoelectronic nonsilicon material on which to fabricate a device. Some obvious advantages are improved mechanical strength and superior thermal conductivity relative to a bulk optoelectronic material.

BRIEF SUMMARY OF THE INVENTION

The invention is a method of forming a virtual substrate comprised of an optoelectronic device substrate and handle substrate comprising the steps of: initiating bonding of the device substrate to the handle substrate; improving or increasing the mechanical strength of the bond between the device and handle substrates; and thinning the device substrate to leave a single-crystal film on the virtual substrate such as by exfoliation of a device film from the device substrate.

The method further comprises the step of providing pre-bonding treatment to allow for the removal of a thin film.

The method still further comprises the step of cleaning and/or passivating the device and/or handle substrates to facilitate bonding.

The step of providing a pre-bonding treatment to allow the removal of a thin film comprises the step of ion implanting the device substrate to inject an amount of gas species into the device substrate to form internally passivated surfaces and to create an internal pressure necessary to exfoliate a layer from the device substrate upon annealing. In the illustrated embodiment ion implanting the device substrate comprises implanting H^+ or a combination of H^+ and He^+.

The step of cleaning and/or passivating the device and handle substrates to facilitate bonding comprises passivating the surface of both the device and handle substrates to allow hydrophobic wafer bonding. The step of passivating the surface of both the device and handle substrates comprises the step of enabling the formation of an intimate covalent bond between a device film, exfoliated from the device substrate, and the handle substrate in the virtual substrate to allow for the low-resistance interface electrical properties. The step of cleaning and/or passivating the device and handle substrates to facilitate bonding comprises the step of eliminating adsorbed water on the surface of the device and handle substrates by means of a low temperature bake in an inert atmosphere or in vacuum. The step of eliminating adsorbed water on the surface of the device and handle substrates by means of a low temperature bake comprising baking at a temperature such that the vapor pressure of water is above the partial pressure of water in the surrounding ambient.

The method further comprises the step of disposing a selected material X on the device substrate to enable an X-to-handle-substrate material bond with the handle substrate when an exfoliated film from the device substrate is bonded with the handle substrate. Material X is any material which is compatible with the claimed methodology and can be determined empirically. The method also further comprises the step disposing a selected material X on the handle substrate to enable an X-to-device-substrate material bond when an exfoliated film from the device substrate is bonded with the handle substrate. The method still further comprises the step of disposing a selected material X on both the device and handle substrates to enable an X-to-X material bond when an exfoliated film from the device substrate is bonded with the handle substrate.

The step of cleaning and/or passivating the device and handle substrates to facilitate bonding comprises the step of removing residual particle contamination on the bonding surfaces of the device and handle substrates. The step of removing residual particle contamination comprises the step of impinging an inert gas on the substrate at an elevated temperature to remove the particles by combined physical impact and thermophoretic lifting effect. Or, alternatively the particles can be removed by exposing the substrates to ultra-sonic or mega-sonic vibrations in a liquid bath.

The step of initiating bonding of the device substrate to the handle substrate comprises the step of controlling the temperature at which the device and handle substrates are brought into contact with each other to select the strain state, whereby substrate performance in high-temperature processes is improved, or a device operation temperature strain selected to adjust a device property such as bandgap or carrier mobility. The step of initiating bonding of the device substrate to the handle substrate comprises the step of

holding the temperature of the device and the temperature of handle substrate when brought into contact with each other at different magnitudes to select the strain state.

In one embodiment, after initiating bonding of the device substrate to the handle substrate, the mechanical strength of the bond between the device and handle substrates is improved and the ion implantation layer transfer process is thermally activated during which uni-axial pressure is applied to the virtual substrate.

The mechanical strength of the bond between the device and handle substrates is improved by using multiple pressure-temperature increments, or continuously varying pressure-temperature combinations. In another embodiment the mechanical strength of the bond of the device to the handle substrate is improved by applying higher pressures to ensure better substrate-substrate contact at lower temperatures prior to exfoliation where the higher pressures would at higher temperatures subdue exfoliation, and then reducing the pressure to a lower level prior to annealing at higher temperatures so that exfoliation is uninhibited.

The method further comprises the step of removing an upper portion of the device film exfoliated from the device substrate, whereby a smoother and less defect prone surface is provided for subsequent optoelectronic device fabrication. The step of removing an upper portion of the device film exfoliated from the device substrate comprises chemically polishing the upper portion with a damage selective etch, or mechanically polishing the upper portion or both. In one embodiment the method further comprises the step of performing homoepitaxy to leave a smooth defect-free surface. In still a further embodiment the method further comprises the step of processing the virtual substrate as a template for growth of an optoelectronic device through hetero-epitaxy.

The invention also includes the virtual substrate which is fabricated according to the forgoing methods.

While the apparatus and method has or will be described for the sake of grammatical fluidity with functional explanations, it is to be expressly understood that the claims, unless expressly formulated under 35 USC 112, are not to be construed as necessarily limited in any way by the construction of "means" or "steps" limitations, but are to be accorded the full scope of the meaning and equivalents of the definition provided by the claims under the judicial doctrine of equivalents, and in the case where the claims are expressly formulated under 35 USC 112 are to be accorded full statutory equivalents under 35 USC 112. The invention can be better visualized by turning now to the following drawings wherein like elements are referenced by like numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram illustrating two alternative fabrication strategies for a virtual substrate.

FIG. **2** is a block diagram illustrated categories of film materials which are used for a virtual substrate according to the invention.

FIGS. **3***a* and **3***b* are diagrams illustrating respectively the ion implantation and the resulting structure in the device substrate.

FIGS. **4***a* and **4***b* are diagrams illustrating respectively the device and handle substrate stack following ion implantation and initial bonding and the wafer bonded virtual substrate following the anneal and layer exfoliation.

FIGS. **5***a* and **5***b* are diagrams illustrating respectively the post-layer transfer device substrate comprised of the near surface ion implantation damage layer and the undamaged bulk, and the removal of the damage by etching from the bulk device substrate allowing the process to be repeated.

FIGS. **6***a* and **6***b* are diagrams illustrating respectively the surface modification of the implanted device substrate with either a film of the same chemical identity as the handle substrate, and a wafer bonded substrate stack using this technique showing the device substrate.

FIG. **7** is a graph of the strain state as a function of temperature for a Ge/Si wafer bonded virtual substrate.

FIG. **8** is a graph of the strain state as a function of temperature for an InP/Si wafer bonded virtual substrate.

FIG. **9** is a graph of the strain state as a function of temperature for a GaAs/Si wafer bonded virtual substrate.

FIG. **10** is a graph of a wafer bonding temperature-pressure curve as a function of time as used in the bond annealing process.

FIGS. **11***a* and **11***b* are diagrams illustrating respectively the wafer bonded virtual substrate following the anneal and layer exfoliation and the wafer bonded virtual substrate following a damage removal etch, polish or epitaxial growth on the device film.

FIG. **12** is a graph of the rms surface roughness of a transferred InP device film as a function of time for 1:2:1, 1:2:2, 1:2:4, and 1:2:5 dilutions of the $HCl:H_3PO_4:H_2O_2$ etch chemistry

FIGS. **13***a* and **13***b* are diagrams illustrating respectively the completed wafer bonded virtual substrate and a wafer bonded virtual substrate with an epitaxially grown device fabricated on the device thin film.

FIG. **14** is a diagram showing an optoelectronic structure grown on a wafer bonded virtual substrate consisting of the device film, the bonded interface, the handle substrate, and a strain compensation layer deposited on the back surface of the substrate.

The invention and its various embodiments can now be better understood by turning to the following detailed description of the preferred embodiments which are presented as illustrated examples of the invention defined in the claims. It is expressly understood that the invention as defined by the claims may be broader than the illustrated embodiments described below.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The fabrication **104** of virtual wafer bonded substrates could take two possible approaches as diagrammatically illustrated in the block diagram of FIG. **1**. These approaches are the integration of a thin device film with a bulk substrate prior to fabricating a functional device indicated by block **100**, or the device film can be transferred to the handle substrate following the fabrication of a functional logic device in the handle substrate and/or the fabrication of a functional optoelectronic device in the optoelectronic device substrate as depicted by block **102**.

This specification summarizes a number of embodiments of the fabrication of optoelectronic virtual substrates. We begin with a summary of the technology generally employed and device structures for which the virtual substrate product can be used. Next, more material process steps are described in the order that they appear in the fabrication process.

Process and Product Overview

For the purpose of the specification the term "device substrate" **10** is the optoelectronic substrate from which a thin film **12** will be removed. The term "handle substrate" **14** is defined in the specification to refer to the substrate that is

used as a mechanical support for the device film **12**, namely the remainder of device substrate **10** after removal of film **12**. The term "virtual substrate" **16** is defined to be the completed structure of a thin device film **12** on a handle substrate **14**.

The materials of interest for device substrate **10** for the discussion below can be considered all materials that are relevant to wafer bonded virtual substrate device film materials for opto-electronic, high-gain device fabrication as illustrated diagrammatically in FIG. **2**: III/V compound semiconductors (i.e. GaAs, InP, GaN, etc.), II/VI semiconductors (i.e. CdTe, etc.), group IV semiconductors (i.e. Ge for GaAs family growth), and optically important Ferroelectric oxides (i.e. $LiNbO_4$, $BaTiO_4$, etc.).

The handle substrate **14** will generally be Si, which is abundantly available and has desirable electrical, mechanical, and thermal properties. However, low-cost insulating substrates (i.e. glass, sapphire, etc.) might also be employed as handle substrate **14**.

A generic process for fabricating such virtual substrates **16** comprises the following steps:

1) The device substrate **10** and handle substrate **14** may need pre-bonding treatment to allow for the removal of a thin film **12** (e.g. ion-implantation into device substrate **10** as diagrammatically depicted by number **11** in FIG. **3***a*).
2) The device substrate **10** is cleaned and/or passivated to facilitate bonding.
3) Bonding is initiated as diagrammatically shown in FIG. **4***a*.
4) The bond **42** is strengthened.
5) The device substrate **10** is thinned to leave a single-crystal film **12** on the finished virtual substrate **16** as shown in FIG. **4***b* for an ion-implanted substrate.
6) In the case of ion implantation induced layer exfoliation, the device substrate **10** from which the device film **12** was derived can be reprocessed by a means of surface polishing to allow the reuse of the substrate **10** to transfer another device film as illustrated in FIG. **5***a* and FIG. **5***b*.

Consider the concepts used for the fabrication of opto-electronic virtual substrates **16**. These will be listed in the order in which they would appear in the generic process described above.

Process Steps

1) Ion Implantation

Prior to bonding, ion implantation of the device substrate **10** is performed to inject a necessary amount of gas species into the substrate to form the internally passivated surfaces and internal pressure necessary to exfoliate a layer from the substrate upon annealing as diagrammatically depicted in FIG. **3***a*, which illustrates pre-bonding ion implantation of the device substrate **10** with an ion beam **11**, creating a modified structure as shown in FIG. **3***b* comprising a device thin film **12**, an ion damaged layer for film transfer **13**, and the largely unaffected bulk of the device substrate **10** which is now called the handle substrate **14**.

This process is generally performed with H^+ or a combination of H^+ and He^+. However, other gas species may be employed to produce an intra-substrate etch process to assist in the exfoliation of the layer. For a given device substrate material there is both a minimum implantation temperature to avoid amorphization and a needed implantation temperature, namely a minimum required dose relationship for this process.

a. H^+ Implantation—A sufficient dose of H^+ is implanted to allow film exfoliation upon annealing. This dose is a function of:
   - Implant energy
   - Implant temperature
   - Device substrate material
   - Film exfoliation anneal temperature

b. H^+/He^+ Co-implantation—A sufficient total dose of H^+ and He^+ is implanted to allow film exfoliation upon annealing. The concept of this approach being that the H plays a chemical role of passivating internal surfaces, while the chemically inert He efficiently migrates to internal surfaces to provide pressure, and creates more damage per implanted ion than H increasing the internal surface density. The necessary dose is a function of:
   - Implant energy
   - Implant temperature
   - H/He ratio
   - Device substrate material
   - Film exfoliation anneal temperature

c. Etchant implantation—In addition to or replacement of H^+ implantation, chemical species known to etch a given material can be implanted to create internally trapped chemical species that are volatile and cause exfoliation upon annealing. The chemical species chosen will be material specific according to known etchant properties or empirical experience.

2) Surface Passivation

Following implantation and prior to bonding, it is necessary to passivate the surface of both the device and handle substrates **10**, **14** to allow hydrophobic wafer bonding. The specific chemical process necessary is device substrate specific. The purpose of this step is to enable the formation of an intimate covalent bond between the device film **12** and handle substrate **14** in the finished virtual substrate **16** allowing for the possibility of ohmic, low-resistance interface electrical properties. A necessary step in enabling this finished device structure will be the elimination of adsorbed water on the surface by means of a low temperature bake in an inert atmosphere or in vacuum. The bake should reach a temperature such that the vapor pressure of water at that temperature is well above the partial pressure of water in the surrounding ambient.

a. Group IV Passivation—The Group IV elemental semiconductors, particularly Ge, are rendered hydrophobic by the use of a dilute HF etching process. This leaves a predominantly hydride terminated surface.

b. Group III/V Passivation—The Group III/V compound semiconductors can be rendered hydrophobic by compound-specific chemical treatments to leave a hydrophobically passivated surface for bonding.

c. Group II/VI Passivation—The Group II/VI compound semiconductors can be rendered hydrophobic by compound-specific chemical treatments to leave a hydrophobically passivated surface for bonding.

d. Ferroelectric Oxides—Applications involving ferroelectric oxides are fundamentally different than those for the optoelectronic materials from the elemental and compound semiconductors. For this reason handle substrate materials will be chosen for their electrical and refractive properties, but there will generally be no need to attempt hydrophobic wafer bonding to the insulating ferroelectric thin films. Thus, surface passivation will generally focus on forming a thin oxide on both the device and handle substrates **10**, **14**.

3) Surface Modification

Another enabling technology for extending this process to a wide range of optoelectronic materials is the use of a deposited surface modification layer **40** of arbitrary thickness to change the nature of the physical interaction between the substrates **10**, **14** as depicted in FIGS. **6***a* and **6***b*. This can be done in one of three ways, where X stands for any type of composition compatible with the disclosed method:

a. Deposition of a layer **40** of material X on the device substrate **10** to enable an X-handle material bond.

b. Deposition of a layer **40** of material X on the handle substrate **14** to enable an X-device material bond.

c. Deposition of a layer **40** of material X on both substrates to enable an X—X bond.

This technology enables the integration of a wide range of optoelectronic materials by mastering bonding with a material which is compatible or amenable to the disclosed process, which for the moment is referenced simply as material X. The generic process is illustrated in FIGS. **6***a* and **6***b*. FIG. **6***a* illustrates the surface modification of the implanted device substrate with either a crystalline or amorphous film **40** of the same chemical identity as the handle substrate **14**. FIG. **6***b* illustrates a wafer bonded substrate stack using this technique showing the device substrate **10**, the ion implanted damage region **13**, the device thin film **12**, the deposited bond mediating film **40**, the bonded interface **42**, and the handle substrate **14**.

More specific applications of this technique are:

d. Epitaxial Si bonding layer—This technique involves epitaxially growing a strained thin film of Si on the device substrate material. In this embodiment material X is strained thin film Si. Through doing this an intimate and maximally strong bond can be ensured between the device material and the Si epitaxial layer. The device substrate **10** with the strained Si epitaxy is then implanted through the epitaxial layer (not shown) in preparation for wafer bonding and layer exfoliation. For material systems utilizing Si handle substrates **14** this would allow direct Si—Si wafer bonding using well established passivation techniques.

e. Amorphous Si bonding layer—This technique involves depositing a thin layer of amorphous Si (not shown) at low temperature on the device substrate **10** to enable the use of typical Si surface preparation chemistries. In this embodiment material X is amorphous Si. This process could be performed either prior to or after ion implantation of the device substrate **10**. For material systems utilizing Si handle substrates **14** this would allow direct Si—Si wafer bonding using well established passivation techniques.

Particle Removal

Following surface passivation, it may be necessary to remove residual particle contamination on the bonding surfaces of the device and handle substrates **10** and **14**. This has been efficiently done by performing a clean with a CO_2 particle jet as depicted in FIGS. **4***a* and **4***b*. FIG. **4***a* is a diagram of a device substrate **10** and handle substrate **14** stack following ion implantation and initial bonding, showing the undamaged bulk device substrate **10**, the ion implanted damage layer **13**, the device thin film **12**, the wafer bonded device/handle interface **42**, and the handle substrate **14**. FIG. **4***b* is a diagram showing the wafer bonded virtual substrate **16** following the anneal and layer exfoliation, and showing the undamaged bulk device substrate **10** with its ion implanted damaged surface region **13**. Also shown is the wafer bonded virtual substrate **16** comprised of the ion implantation damaged surface region **13** of the device film **12**, the undamaged transferred device film **12**, the wafer bonded interface **42**, and the handle substrate **14**. The substrates **10** and/or **14** are held at an elevated temperature and a throttled gas/particle jet of CO_2 is impinged on the surface of substrates **10**, **14** removing particles by a combined physical impact and thermophoretic lifting effect.

This has been demonstrated for Si, Ge, and InP by maintaining the substrates at a temperature greater than 50° C. during application of the CO_2.

5) Elevated Temperature Bond Initiation

When bonding dissimilar materials there is generally a coefficient of thermal expansion mismatch between the two materials resulting in a temperature-dependent strain state of the device thin film **12** in the virtual substrate **16** that is governed by the equation

$$\gamma(T) = \int_{T_0}^{T} \Delta\alpha(T')dT'$$

where $\Delta\alpha(T)$ is the difference in the thermal expansion coefficients α between the two substrates as a function of temperature, T, and where T_0 is the temperature of the zero strain condition, typically assumed to be the bond initiation temperature. Thus, by controlling the temperature at which two substrates are brought into contact, the strain state at temperatures of interest can be engineered. This could be advantageous for improving substrate performance in high-temperature processes, or a device operation temperature strain could be engineered to adjust a key device property such as bandgap or carrier mobility. The following descriptions describe the general types of strain temperature-strain dependences that could be achieved as a function of the sign of $\Delta\alpha(T)$.

$$\Delta\alpha(T)=\alpha_{handle}(T)-\alpha_{device}(T)$$

Such that positive values of strain indicate a film in tension and negative values of strain indicate a film in compression.

a. $\Delta\alpha(T)>0$:

1. Room Temperature Bonding—In this case the film **12** will be in tension at elevated processing temperatures. This will lead to changes in the lattice matching in heteroepitaxy on the virtual substrate **16** and a tendency to concave substrate bowing.
2. Elevated Temperature Bonding—In this case the film will have a zero strain condition at the bonding temperature such that tensile strain and concave wafer bowing will be reduced at higher processing temperatures. Likewise, the film **12** will be in compressive strain at room temperature and likely at device operating temperatures leading to convex wafer bow. This could change device operation and enable design of novel devices based on strain control of materials parameters.

b. $\Delta\alpha(T)<0$:

1. Room Temperature Bonding—In this case the film will be in compression at elevated temperatures. This will lead to changes in the lattice matching in heteroepitaxy on the virtual substrate and a tendency to convex substrate bowing.
2. Elevated Temperature Bonding—In this case the film **12** will have a zero strain condition at the bonding temperature such that compressive strain and convex bowing will be reduced at higher processing temperatures. Likewise, the film **12** will be in tensile

strain at room temperature and likely at device operating temperatures leading to concave wafer bow. This could change device operation and enable design of novel devices based on strain control of materials parameters. Most materials of interest for the wafer bonded virtual substrates **16** described belong to this category.

a. Ge/Si Bonding—FIG. **7** is a graph which illustrates the predicted strain in Ge/Si bonding as a function of temperature for substrates bonded at various values of T_0. The film compression at high temperatures can be reduced by initiation bonding at higher temperatures, T_0.

b. InP/Si Bonding—FIG. **8** is a graph which illustrates the predicted strain in InP/Si bonding as a function of temperature for substrates bonded at various values of T_0. Again, the film compression at high temperatures can be reduced by initiation bonding at higher temperatures, T_0.

c. GaAs/Si Bonding—FIG. **9** is a graph which illustrates the predicted strain in GaAs/Si bonding as a function of temperature for substrates bonded at various values of T_0. Once again, the film compression at high temperatures can be reduced by initiation bonding at higher temperatures, T_0.

6) Dissimilar Temperature Bond Initiation

For some desired engineered stain states, no single elevated bond temperature will enable the fabrication of that device. Likewise, for materials with very similar coefficients of thermal expansion strain engineering will be difficult. To further enable control of strain at a desired temperature, bonding could be initiated between substrates held at different temperatures. In this way, the thermo-mechanical strain state could be more freely controlled or artificially built into the finished structure. In this case the temperature dependent strain state is given by

$$\gamma(T) = \int_{T_0}^{T} \Delta\alpha(T')dT' + \gamma_0$$

where the value γ_0 is the strain built into the bonded structure upon bond initiation and is given by

$$\gamma_0 = \int_{T_0}^{T_d} \alpha_d(T')dT' + \int_{T_h}^{T_0} \alpha_h(T')dT'$$

In this expression, T_d and T_h are the temperatures of the device substrate **10** and the handle substrate **14** respectively at the instant of bond initiation. The temperature T_0 is the effective bond initiation temperature. The dissimilar temperatures of the substrates at bond initiation make this term difficult to determine. T_0 must have a value between T_d and T_h and will depend upon the experimental apparatus used in fabrication of the virtual substrate **16** and can be determined experimentally. The built-in strain approaches

$$\gamma_0 = \int_{T_h}^{T_d} \alpha(T')dT'$$

for device and handle substrates **10**, **14** with very similar coefficients of linear expansion. Bonding at different wafer temperatures can be conducted in the following circumstances.

a. $\Delta\alpha(T)>0$:
   1. $T_d>T_h$—These conditions enable the addition of a positive stress component causing the device film to be under increased tension at elevated temperatures.
   2. $T_d<T_h$—These conditions enable the addition of a negative stress component reducing the high temperature tensile stress, but creating a greater low temperature compressive stress.

b. $\Delta\alpha(T)<0$:
   1. $T_d>T_h$—These conditions enable the addition of a positive stress component causing the device film to be under a reduced degree of compressive stress at high temperatures.
   2. $T_d<T_h$—These conditions enable the addition of a negative stress component increasing the high temperature compressive stress, but creating a reduced low temperature tensile stress.

c. $\Delta\alpha(T)=0$:
   1. $T_d>T_h$—A temperature independent tensile stress can be imparted on the device film in this way.
   2. $T_d<T_h$—A temperature independent compressive stress can be added to the device film.

7) Annealing Under Pressure to Strengthen Bonding and Exfoliate the Device Layer-

After the device and handle substrates **10**, **14** have been bonded, it is necessary to use a thermal cycle to improve bond strength and to activate the ion implantation layer transfer process. By performing this cycle under pressure, thermo-mechanical strain can be accommodated in the bonded bulk substrate stack. Additionally, bonding is strengthened by means of improved substrate-substrate contact. A bonding process using multiple pressure-temperature steps or even a continuously varying pressure-temperature curve can be used to optimize the effectiveness of pressure in the process.

Specifically, at lower temperatures prior to exfoliation, higher pressures can be employed to ensure better substrate-substrate contact, but these pressures would at higher temperatures subdue exfoliation. By reducing the pressure to a lower level prior to annealing to high temperatures, exfoliation is uninhibited.

a. Variable Pressure Cycle—One possible embodiment is to utilize independently varied pressure and temperature to optimize the bonding process. At low temperatures, high pressures are applied to strengthen the bond. At high temperatures the pressure is then reduced to avoid the suppression of layer exfoliation in the device substrate. A representative process is illustrated in the graph of FIG. **10** where the wafer bonding temperature-pressure curve is shown as a function of time in the bond annealing process.

b. Single Pressure Cycle—The bonding process is also improved by applying a uni-axial load to the bonded pair for the duration of the anneal. In this process it is essential that the load be small enough to avoid the suppression of blistering.

8) Device Layer Modification

Following the transfer of the device film in the ion implantation induced layer transfer process, the near surface region of the device film **12** is both rough and defect rich. This layer must be controllably removed to leave a surface that is useful for subsequent processing to fabricate an

optoelectronic device as shown in FIGS. **11***a* and **11***b*. Depending on the device layer **10** this can be accomplished by:

a. Wet Chemical Polishing—This process uses a device-film-dependent etch to controllably remove the ion implantation induced damage layer **13** of the wafer bonded virtual substrate **16**, while simultaneously smoothing the surface of the transferred layer. Etches for specific materials are given below.

1. Ge/Si:
   i. $HF:H_2O_2:H_2O$—This etch can be performed at various dilution ratios x:y:z at various temperatures.
   ii. $HF:HNO_3:C_2H_4O_2:H_2O$—This etch can be performed at various dilution ratios w:x:y:z at various temperatures.
   iii. $H_2O_2:H_2O$—This etch can be performed at various dilution ratios y:z at various temperatures.
2. InP/Si:
   i. $HCl:H_3PO_4:H_2O_2$—This etching solution has been successfully used in ratios of 1:2:2 and 1:2:4. The H_2O_2 acts as an oxidizing agent and the mixture of HCl and H_3PO_4 etches the oxide. The combination of oxidation followed by etching creates a smoothened surface and removes the implantation damage. FIG. **12** is a graph which shows both the surface roughness as a function of time for various etch dilutions.

b. Chemical Mechanical Polishing—This utilizes both a chemical and a mechanical slurry to etch through implantation damage and leave a smooth surface.

1. Ge/Si—A colloidal silica slurry in a KOH chemistry can be used to polish the substrate.
2. InP/Si—A colloidal silica slurry in a sodium hypochlorite solution has been shown to smooth the surface of these virtual substrate materials.

c. Homoepitaxial Smoothing—Even in circumstances when chemical etching removes the implantation damage, but doesn't leave an optimally smooth surface for subsequent heteroepitaxy, homoepitaxy of the device film material on the etched sample has been shown to reduce surface roughness. This can be performed as the first step in the growth of a heteroepitaxial structure on the wafer bonded virtual substrate.

9) Epitaxial Heterostructure Growth

The finished virtual substrate **16** is meant to serve as a template for growth of an optoelectronic device through hetero-epitaxy. Through careful device layer modification, epitaxy of a wide range of optoelectronic devices is made possible. A representative image of such a structure is shown in FIGS. **13***a* and **13***b*. FIG. **13***a* is a diagram which shows the completed wafer bonded virtual substrate **16** comprised of a thin device film **12**, a wafer bonded interface **42** and a handle substrate **14**. FIG. **13***b* is a diagram which shows a wafer bonded virtual substrate **16** with an epitaxially grown device **50** fabricated on the device thin film **12**.

10) Strain Compensation Layer

One potential challenge in implementing wafer bonded virtual substrates in the fabrication of devices in or on the transferred layer by standard processing such as MOCVD, diffusion, implantation, and lithography is the possibility of wafer bow due to the presence of thermal expansion derived strain in the transferred layer. A practical approach to minimizing this effect would be to deposit a strain compensation layer on the back surface of the handle substrate **14** as shown in FIG. **14**. FIG. **14** is a diagram which schematically shows an optoelectronic structure **50** grown on a wafer bonded virtual substrate **16** comprised of the device film **12**, the bonded interface **42**, the handle substrate **14**, and a strain compensation layer **18** deposited on the back surface of the substrate.

This concept would be implemented by depositing a thin film **18** on the back surface of the handle substrate **14** either prior to or after the transfer of the device layer **10** to the handle substrate **14**. The strain compensation layer **18** must have the same sign of $\Delta\alpha$ relative to the handle substrate as the device film **12**. The zero bow condition is not a zero strain condition, but rather a condition in which the strain energy of the device film **12** and the strain compensation layer **18** are exactly matched providing no driving force for substrate deformation. The material and deposition technique can be chosen to minimize the fabrication cost associated with this processing step. The strain energy associated with a thin film **12** is increased with substrate diameter, film strain, and film thickness. The strain compensation layer material **18**, deposition temperature, and thickness can be chosen to tailor the zero bow process temperature. The following are examples of how strain compensation could be performed for several materials systems:

a. Ge/Si—The simplest case would be to deposit a film of Ge on the back surface of the Si handle substrate.
b. InP/Si—Rather than deposit InP on the back of the handle, a thin film of Ge could be utilized because of its ease of deposition.
c. GaAs/Si—As in the InP/Si case, Ge would make a good strain compensation layer.
d. Other Materials—For all of the systems mentioned above, a low-cost material that is easily deposited is a suitable strain compensation layer, provided that the sign of $\Delta\alpha$ is appropriate.

Many alterations and modifications may be made by those having ordinary skill in the art without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiment has been set forth only for the purposes of example and that it should not be taken as limiting the invention as defined by the following claims. For example, notwithstanding the fact that the elements of a claim are set forth below in a certain combination, it must be expressly understood that the invention includes other combinations of fewer, more or different elements, which are disclosed in above even when not initially claimed in such combinations.

The words used in this specification to describe the invention and its various embodiments are to be understood not only in the sense of their commonly defined meanings, but to include by special definition in this specification structure, material or acts beyond the scope of the commonly defined meanings. Thus if an element can be understood in the context of this specification as including more than one meaning, then its use in a claim must be understood as being generic to all possible meanings supported by the specification and by the word itself.

The definitions of the words or elements of the following claims are, therefore, defined in this specification to include not only the combination of elements which are literally set forth, but all equivalent structure, material or acts for performing substantially the same function in substantially the same way to obtain substantially the same result. In this sense it is therefore contemplated that an equivalent substitution of two or more elements may be made for any one of the elements in the claims below or that a single element may be substituted for two or more elements in a claim. Although elements may be described above as acting in certain combinations and even initially claimed as such, it is

to be expressly understood that one or more elements from a claimed combination can in some cases be excised from the combination and that the claimed combination may be directed to a subcombination or variation of a subcombination.

Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

The claims are thus to be understood to include what is specifically illustrated and described above, what is conceptionally equivalent, what can be obviously substituted and also what essentially incorporates the essential idea of the invention.

We claim:

1. A method of forming a virtual substrate comprising: (1) treating a surface of at least one of a device substrate and a handle substrate to prepare the at least one of the device substrate and the handle substrate for formation of a low resistance electrical contact between the device substrate and the handle substrate in a subsequent step; (2) bonding the device substrate to the handle substrate to form a bonded interface having the low resistance electrical contact between the device substrate and the handle substrate; (3) removing a portion of the device substrate so as to leave a device film on the handle substrate; and (4) forming a strain compensation layer on a back surface of the handle substrate prior to bonding a front surface of the handle substrate to the device substrate.

2. The method of claim **1**, further comprising ion implanting the device substrate prior to bonding to enable exfoliation of the device film from the device substrate by annealing the device substrate after the bonding step.

3. The method of claim **2**, wherein the step of removing comprises annealing the device substrate to exfoliate the device film from the device substrate.

4. The method of claim **1**, wherein the step of treating comprises at least of one of passivating and cleaning.

5. The method of claim **1**, wherein the bonded interface between the device film and handle substrates comprises covalent bonds between the device substrate and the handle substrate.

6. The method of claim **1**, wherein the bonded interface between the device film and handle substrate has a resistivity of 3.5 ohms cm^2 or less.

7. The method of claim **3**, further comprising performing a post bonding thermal anneal to strengthen a bond between the device film and handle substrate prior to performing the exfoliation anneal.

8. The method of claim **2**, wherein the step of ion implanting the device substrate comprises implanting H^+, He^+, or a combination of H^+ and He^+.

9. The method of claim **4**, wherein the steps of treating the surfaces of the device and handle substrates comprises passivating the surfaces of both the device and handle substrates to allow for hydrophobic wafer bonding.

10. The method of claim **1**, wherein the step of treating the surfaces of the device and handle substrates comprises rendering the surfaces substantially hydrophobic prior to bonding.

11. The method of claim **10**, wherein the step of treating comprises treating the handle and device substrate surfaces with HF solution.

12. The method of claim **11**, wherein the HF solution reduces or eliminates oxides on the handle and device substrate surfaces.

13. The method of claim **1**, wherein the step of treating comprises eliminating adsorbed water on the surface of at least one of the device substrate and the handle substrate by exposure of the surface to an inert atmosphere or vacuum prior to bonding.

14. The method of claim **13**, wherein eliminating adsorbed water comprises baking at a temperature such that a vapor pressure of water on at least one substrate surface is above a partial pressure of water in the surrounding environment.

15. The method of claim **1**, wherein the device film comprises a Ge, a Group II-VI, a Group III/V or a SiC semiconductor material and the handle substrate comprises a Si or a GaAs substrate.

16. The method of claim **1**, wherein the device film comprises a Group III-V film.

17. The method of claim **1**, wherein the bonded interface has a resistance of 35 ohms or less over a 0.1 cm^2 evaluation area.

18. The method of claim **1**, wherein the bonded interface exhibits ohmic characteristics.

19. The method of claim **1**, wherein a coefficient of thermal expansion (CTE) difference between the strain compensation layer and the handle substrate is of a same sign as a CTE difference between the device film and the handle substrate, and at least one strain compensation layer property is selected to control a bow of the virtual substrate over a given temperature range.

20. The method of claim **19**, wherein the step of bonding occurs at an elevated temperature to reduce the bow of the virtual substrate at elevated temperatures.

21. The method of claim **1**, further comprising epitaxially growing at least one semiconductor layer on the device film and forming a semiconductor device comprising the at least one semiconductor layer.

22. The method of claim **1**, wherein the device substrate comprises a semiconductor substrate and the handle substrate comprises a semiconductor substrate.

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