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United States Patent	12389718
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Fitzgerald; Eugene A. et al.

Method for fabricating a semiconductor device including integrating III-V device and CMOS device, and the semiconductor device thereof

Abstract

A method of fabricating a semiconductor device (200) is described. According to a described embodiment, the method comprises: (i) forming a III-V semiconductor material layer (206) comprising a substrate layer (208) and a device layer (210) attached to the substrate layer (208); and (ii) forming an electrically conductive interlayer (228) to the device layer (210) prior to bonding the electrically conductive interlayer (228) to a partially processed CMOS device layer (204) having at least one transistor (205).

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Appl. No.:	17/640547
Filed (or PCT Filed):	September 25, 2020
PCT No.:	PCT/SG2020/050544
PCT Pub. No.:	WO2021/061052
PCT Pub. Date:	April 01, 2021

Prior Publication Data

Document Identifier	Publication Date
US 20220293820 A1	Sep. 15, 2022

Related U.S. Application Data

us-provisional-application US 62906986 20190927

Publication Classification

Int. Cl.: H10H20/824 (20250101); H01L25/16 (20230101); H10H20/833 (20250101)

U.S. Cl.:

CPC H10H20/824 (20250101); H01L25/167 (20130101); H10H20/833 (20250101);

Field of Classification Search

CPC: H01L (33/30); H01L (33/42); H10H (20/0133); H10H (20/018); H10H (20/824); H10H (20/833); H10H (20/857); H10D (84/08)

USPC: 257/103

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a U.S. National Stage of International Application No. PCT/SG2020/050544 filed on Sep. 25, 2020, which claims priority to U.S. Application No. 62/906,986, filed on Sep. 27, 2019, the disclosures of which are incorporated herein by reference as if set forth in their entireties.

TECHNICAL FIELD

(1) The present disclosure relates to a method for fabricating a semiconductor device and also the semiconductor device.

BACKGROUND

(2) Numerous methods have been used to integrate Complementary Metal Oxide Semiconductor (CMOS) integrated circuits with other specialized integrated circuits such as those which include III-V devices. Most of these methods merge the integrated circuits at a package-level which involve a parallel integrated process flow by which the III-V devices are processed in parallel on separate wafers from CMOS devices, and are subsequently merged and interconnected at the chip or wafer-level after device fabrication. A more desirable approach is to integrate these integrated circuits monolithically, which potentially reduces packaging size and costs. In contrast to the package-level integration method, monolithic integration processes involve a serial sequence where all devices are fabricated in various sequential steps on a wafer flow and then interconnected all at once using a back-end process, for example, a back-end silicon CMOS process.

(3) Various monolithic processes to integrate III-V materials with CMOS involve III-V devices that can emit or detect visible light. An example of such a monolithic process is shown in FIG. 1. FIG. 1 shows a side-by-side configuration **100** of a top CMOS “front-end” transistor layer **102** and a multi-layer III-V optoelectronic device **104** used in an existing art. Note that the “back-end” of a CMOS chip (e.g. interconnect layers and dielectrics connecting CMOS transistors of the CMOS transistor layer **102** to the III-V optoelectronic device **104** and other CMOS transistors) is not shown for simplicity. In this side-by-side configuration **100**, the silicon CMOS transistor layer **102** and the III-V device **104** cannot occupy a same area from a plan-view wafer perspective (i.e. when viewing from a top side of the wafer). This side-by-side configuration **100** of FIG. 1 is typically used because the III-V device **104** is processed when a top silicon layer (not shown) originally on top of the buried III-V epitaxial stacks **106** is removed. Once the top silicon layer above the buried

III-V epitaxial stacks **106** is removed (e.g. by etching), the buried III-V device layers **106** can be processed with standard top-down process steps such as etching and deposition to form the III-V device **104**. It is clear that these process steps cannot proceed when the buried III-V device layers **106** are covered initially with the top silicon layer being in place. As shown in FIG. **1**, this process also leaves buried III-V device layers **108** underneath the top CMOS “front end” transistor layer **102** unprocessed. Further, the III-V device **104** is required to operate from a top-side (i.e. an opposite side to a silicon substrate **110**) to avoid absorption of visible light by the silicon substrate **110** since an efficient emission area **112** of the III-V device **104** may not exist underneath a top silicon layer. Thus, there is a device density limit for the monolithic process configuration **100** of FIG. **1**.

(4) Besides having the device density limit, the required topside emission or detection of the optoelectronic III-V device **104** means that such III-V optoelectronic device **104** being introduced in this side-by-side configuration as shown in FIG. **1** would have more restricted design requirements. For example, in an embodiment where the III-V device **104** is a III-V light emitting diode (LED), it is necessary to design the epitaxial layer stack **106** defining the LED structure and the contact metallization **114** on top of the LED to allow as much light **116** to be directed upwards as possible. As shown in FIG. **1**, for example, the contact metallization **114** to the LED is required to have an opening in it, i.e. a window in the electrical contact, in order to allow transmission of light **116** out of the LED. The window in the contact metallization **114** is exemplified by a top-view **117** of an annular shape of the contact **114** as shown in FIG. **1**. This necessity introduces a trade-off between efficient current injection across an entire LED and how much light **116** can be transmitted from a top-side of the LED. In addition, the back-end interconnects in the silicon integrated circuit (not shown) have to be routed around the LED emission area **112** so that these interconnects do not block the emitted light **116**.

(5) The significance of the current injection versus light emission trade-off at the top-side of the LED described above largely depends on an ability of the current to spread sideways in the top p.sup.+ semiconductor layer **118** of the III-V device layers **106**. In an embodiment where the III-V device is a GaN LED, the top p.sup.+ GaN layer is typically doped with magnesium (Mg) and has a high lateral resistance when compared to n.sup.+ GaN or a metal. Thus, in this case, there is considerable penalty for eliminating some metallization at the top-side for the GaN LED. Therefore, the side-by-side configuration **100** of the prior art creates both LED inefficiency as well as a reduced, sub-optimal, device density. It is therefore desirable to provide a method for fabricating a semiconductor device and a semiconductor device which address the aforementioned problems and/or provides a useful alternative.

(6) Furthermore, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

SUMMARY

(7) Aspects of the present application relate to a method for fabricating a semiconductor device and also the semiconductor device, in particular, a semiconductor device which includes an electrically conductive interlayer formed between a CMOS device layer and a III-V device layer.

(8) In accordance with a first aspect, there is provided a method of fabricating a semiconductor device, comprising: (i) forming a III-V semiconductor material layer comprising a substrate layer and a device layer attached to the substrate layer; and (ii) forming an electrically conductive interlayer to the device layer prior to bonding the electrically conductive interlayer to a partially processed CMOS device layer having at least one transistor.

(9) By forming the electrically conductive interlayer to the device layer prior to bonding the electrically conductive interlayer to the partially processed CMOS device layer, a contact resistance of a III-V device included in the device layer of the III-V semiconductor material layer is reduced. Further, with the formation of the electrically conductive interlayer, the III-V device included in the

III-V device layer can be located below (or covered by) the partially processed CMOS layer due to the high lateral conductivity of the electrically conductive interlayer. This leads to an increase in a device density of the semiconductor device integrating CMOS and III-V devices. Particularly, the ultimate density of a III-V+CMOS device circuit has a limit defined by an area occupied by the silicon CMOS and an area occupied by the interconnects required for connecting the CMOS devices to the III-V devices. This assumes that negligible space is consumed by the III-V device. With respect to the prior art side-by-side configuration **100** as shown in FIG. **1**, the assumption of negligible space consumed by the III-V device does not hold true. In contrast, as discussed above, the present method enables the III-V device included in the III-V device layer to be located below the partially processed CMOS layer, so that an effective area for the III-V+CMOS circuit includes only the silicon CMOS area and the area for the interconnects in order to achieve the ultimate density for a III-V+CMOS device circuit.

(10) Further, with an increased device density, lower integrated circuit cost can be achieved. This is because a higher device density will enable more chips to be fabricated per wafer, thereby lowering a fabrication cost of each integrated circuit. In addition, formation of the electrically conductive interlayer provides a higher degree of freedom for designing a layout of the back-end interconnects, since the III-V device included in the III-V device layer can be located below the partially processed CMOS layer. Details on the layout and how at least some of these advantages are achieved are discussed below in relation to FIG. **2**.

(11) The method may comprise bonding the electrically conductive interlayer to the partially processed CMOS device layer.

(12) Forming the III-V semiconductor material layer may include epitaxially depositing the device layer on the substrate layer.

(13) The device layer may include an optoelectronic device having a top device surface, a bottom device surface and an active optical area between the top device and bottom device surfaces; the bottom device surface being attached to the substrate layer and passage of light is via the bottom device surface.

(14) The substrate layer may include a light transmissible substrate.

(15) The method may comprise removing the substrate layer after the CMOS device layer is bonded to the electrically conductive interlayer.

(16) The method may comprise bonding a light transmissible substrate to the bottom device surface of the optoelectronic device after removal of the substrate layer. With the removal of the substrate layer, the light transmissible substrate serves to provide structural support for the semiconductor device and allow light to pass through via the bottom device surface.

(17) The method may comprise forming vias and metal lines to electrically connect the at least one transistor of the CMOS device layer to the optoelectronic device.

(18) The method may comprise depositing a bonding material to the electrically conductive interlayer prior to bonding the CMOS device layer to the electrically conductive interlayer, and the method may comprise chemo-mechanically polishing the bonding material. Depositing a bonding material and chemo-mechanically polishing the bonding material advantageously improves an adhesion between the CMOS device layer and the electrically conductive interlayer when the CMOS device layer is bonded to the electrically conductive interlayer.

(19) The electrically conductive interlayer may include indium tin oxide.

(20) In accordance with a second aspect, there is provided a semiconductor device, the semiconductor device comprising: a partially processed CMOS device layer having at least one transistor; a III-V semiconductor material layer comprising a substrate layer and a device layer attached to the substrate layer; and an electrically conductive interlayer attached to and sandwiched between the partially processed CMOS device layer and the device layer.

(21) The device layer may include an optoelectronic device having a top device surface, a bottom device surface, and an active optical area between the top device and bottom device surfaces, the

bottom device surface being attached to the substrate layer and passage of light is via the bottom device surface.

(22) The substrate layer may include a light transmissible substrate. The light transmissible substrate serves to provide structural support for the semiconductor device and allow light to pass through via the bottom device surface.

(23) It should be appreciated that features relating to one aspect may be applicable to the other aspects. Embodiments therefore provide a method of fabricating a semiconductor device comprising forming the electrically conductive interlayer to the device layer of the III-V semiconductor material layer prior to bonding the electrically conductive interlayer to the partially processed CMOS device layer. This advantageously achieves a lower contact resistance for the III-V device included in the device layer of the III-V semiconductor material layer. With the formation of the electrically conductive interlayer, the III-V device included in the III-V device layer can be located below the partially processed CMOS layer due to the high lateral conductivity (e.g. less than 100 Ohm/sq) of the electrically conductive interlayer. This leads to an increase in a device density of the semiconductor device integrating CMOS and III-V devices. In addition, with an increased device density, lower integrated circuit cost can be achieved. Further, the formation of the electrically conductive interlayer provides a higher degree of freedom for designing a layout of the back-end interconnects, since the III-V device included in the III-V device layer can be located below the partially processed CMOS layer.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Embodiments will now be described, by way of example only, with reference to the following drawings, in which:
- (2) FIG. 1 shows a schematic structure of a side-by-side configuration for monolithic integration of III-V and CMOS devices according to a prior art;
- (3) FIG. 2 shows a schematic structure of a semiconductor device integrating CMOS and III-V devices in accordance with a first embodiment, where an electrically conductive interlayer is formed between a partially processed CMOS device layer and a device layer of the III-V semiconductor material layer;
- (4) FIG. 3 shows a schematic structure of a semiconductor device integrating CMOS and III-V devices in accordance with a second embodiment, where the III-V device is a light-emitting diode (LED) and at least a substrate layer of the III-V semiconductor material layer has been removed to allow light to escape from a bottom-side of the semiconductor device;
- (5) FIG. 4 shows a schematic structure of a semiconductor device integrating CMOS and III-V devices similar to that of FIG. 3 but with the substrate layer of the III-V semiconductor material layer being replaced by a light transmissible substrate instead of it being removed, in accordance with a third embodiment;
- (6) FIG. 5 is a flowchart showing steps of a method for fabricating the semiconductor devices of FIGS. 2 to 4 in accordance with an embodiment;
- (7) FIG. 6 shows a top plan-view of a circuit layout according to the side-by-side configuration used in the prior art of FIG. 1;
- (8) FIG. 7 shows a top plan-view of a circuit layout according to an embodiment which incorporates configurations of the semiconductor devices of FIGS. 2 to 4; and
- (9) FIG. 8 shows a cross-sectional electronic microscopy (EM) image of an actual semiconductor device fabricated, the actual semiconductor device having a similar structure as shown in FIG. 2.

DETAILED DESCRIPTION

- (10) Exemplary embodiments relate to a method for fabricating a semiconductor device and also

the semiconductor device, in particular, a semiconductor device which includes an electrically conductive interlayer formed between a CMOS device layer and a III-V device layer.

(11) FIG. 2 shows a schematic structure **200** of a semiconductor device **202** integrating CMOS and III-V devices in accordance with a first embodiment. Depending on a specific type and/or application of the III-V device which is integrated in the semiconductor device, variations of a structure of the semiconductor device **202** exist and these are discussed in relation to FIGS. 3 and 4. In all the FIGS. 2 to 4, back end metallization is not shown for clarity.

(12) The semiconductor device **202** comprises a partially processed CMOS device layer **204** having at least one transistor **205** and a III-V semiconductor material layer **206**. In the present embodiment, the partially processed CMOS device layer **204** includes silicon CMOS front-end transistors formed on a Si (100) substrate, and have a thickness of about 1000 nm, although other types of CMOS devices may be included in the partially processed CMOS device layer **204** of a different thickness. The III-V semiconductor material layer **206** comprises a substrate layer **208** and a device layer **210** attached to the substrate layer **208**. In an embodiment, the device layer is epitaxially deposited on the substrate layer **208**, for example by molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD) techniques. The substrate layer **208** comprises a silicon (Si) (111) substrate in the present embodiment, although other CMOS-compatible substrate may be used. The Si (111) substrate is about 725 μm thick. In the present embodiment as shown in FIG. 2, the semiconductor device **202** also includes, optionally, a buffer layer **212** sandwiched between the substrate layer **208** and the device layer **210**. The buffer layer **212** serves to reduce propagation of defects generated, for example, as a result of lattice mismatch between the substrate layer **208** and the device layer **210**. The buffer layer **212** is commonly used in III-V-on-silicon substrate, for example a GaN-based device layer on a silicon substrate, due to the difference in their crystal lattice constants. For example, in a GaN-on-silicon substrate, the buffer layer **212** may include sub-buffer layers **214**, **216** such as a graded AlGaIn buffer layer **214** and an undoped GaN buffer **216**. In another example, for a GaAs-on-silicon substrate, a Ge/GaAs buffer layer **212** may be used. In other embodiments, a buffer layer **212** is not required and so the substrate layer **208** may be directly attached to the device layer **210**.

(13) The device layer **210** includes a III-V device **217**. The III-V device **217** may be an electronic device or an optoelectronic device. A III-V electronic device and a III-V optoelectronic device may share a similar device structure, except that the III-V optoelectronic device which involves receiving and transmitting light will require at least a partially unblocked active optical area for emitting and/or receiving light. In the present embodiment as shown in FIG. 2, the III-V device **217** comprises an active layer **218** formed between a top device electrode layer **220** and a bottom device electrode layer **222**. As shown in FIG. 2, the active layer **218** includes multiple material layers, for example, an active electronic layer for an electronic device (e.g. a heterojunction bipolar transistor (HBT) or a high electron mobility transistor (HEMT)) or an active optoelectronic layer for an optoelectronic device (e.g. a light emitting diode or a laser). In an embodiment where the III-V device is a GaAs HBT, the top device electrode layer **220** and the bottom device electrode layer **222** may each include an n-doped GaAs layer. The top device electrode layer **220** therefore forms a top device surface **224** and the bottom device electrode layer **222** forms a bottom device surface **226**. As shown in FIG. 2, the top device surface **224** and the bottom device surface **226** of the present embodiment are planar surfaces. In the present embodiment where the substrate layer **208** includes the Si (111) substrate which is not optically transparent, the III-V device **217** includes an electronic device which does not require receiving and/or emitting light. However, as would be appreciated by a skilled person in the art, even if the substrate layer **208** includes the Si (111) substrate, and that the III-V device is fully under the CMOS device layer **204**, the fact that the interconnects (e.g. tungsten plugs/pads **232**) are not blocked by the CMOS device layer **204** means that there may be gaps between the CMOS device layer **204** and the interconnects. Therefore, even in this case, light can scatter out of these gaps. Thus, it is possible that in some embodiments, even

if the substrate layer **208** includes the Si (111) substrate, the III-V device **217** may include an optoelectronic device. While light emission in these embodiments is poorer, it may still be sufficient for certain applications (e.g. where the light is used as an indicator, or for low-level illumination). In another embodiment, the substrate layer **208** of the III-V semiconductor material layer **206** includes a light transmissible or optically transparent substrate. In this embodiment, the III-V device **217** may include an optoelectronic device since light can be emitted or received through the light transmissible or optically transparent substrate at the bottom side of the III-V device **217**. Embodiments where the III-V device layer **210** comprises a III-V optoelectronic device, such as a LED, are discussed in relation to FIGS. **3** and **4** below.

(14) As shown in FIG. **2**, an electrically conductive interlayer **228** is attached to the device layer **210** and is sandwiched between the partially processed CMOS device layer **204** and the device layer **210**. This electrically conductive interlayer **228** is applied across the device layer **210** before the front-end CMOS layer **204** is transferred onto the III-V semiconductor material layer **206** since it is not possible to form the electrically conductive interlayer **228** laterally once the front-end CMOS layer **204** is in place, given that there is no process-access to the III-V device layer **210** for the rest of the fabrication process at any regions where the front-end CMOS layer **204** remains. Although the electrically conductive interlayer **228** is shown in FIG. **2** as a single layer, the electrically conductive interlayer **228** may also comprise a plurality of conductive layers. The electrically conductive interlayer **228** may comprise a metal or a conductive oxide such as indium tin oxide (ITO), or a combination of the two.

(15) In the present embodiment, a bonding material **230** such as silicon dioxide (SiO₂) is deposited on the electrically conductive interlayer **228** before the partially processed CMOS device layer **204** is bonded to the electrically conductive interlayer **228**. The bonding material **230** may be chemo-mechanically polished before the partially processed CMOS device layer **204** is bonded to the electrically conductive interlayer **228**. The bonding material **230** may have a thickness of about 500 nm.

(16) Once the partially processed CMOS device layer **204** is bonded to the III-V semiconductor material layer **206** as shown in FIG. **2**, a conductive plug **232** (e.g. tungsten plugs) can be formed on each of the top and bottom device electrode layers **220**, **222** for electrically contacting the III-V device **217**. A top surface of these conductive plugs **232** are approximately co-planar with the silicon CMOS front-end transistors of the partially processed CMOS device layer **204** as shown in FIG. **2**. The integrated semiconductor device **202** can then be encapsulated by another insulating material **234** (e.g. SiO₂). A typical thickness of this insulating material **234** formed above the CMOS device layer **204** is about 800 nm. Back-end silicon CMOS processes can be performed to interconnect the at least one transistor **205** of the CMOS device layer **204** with the III-V device **217** to form an integrated circuit. For example, vias and metal lines can be formed to electrically connect the at least one transistor **205** of the partially processed CMOS device layer **204** to the III-V device **217**. This may include forming a further conductive plug (e.g. a metal plug) on either the at least one transistor **205**, or on the conductive plug electrically contacting the device electrode layers **220**, **222** of the III-V device **217**.

(17) As shown in FIG. **2**, a substantial part of the III-V device layer **210** can be overlapped with the partially processed CMOS device layer **204**. In other words, a higher device density can be achieved as compared to the side-by-side configuration previously shown in FIG. **1**. This advantage is provided by the electrically conductive interlayer **228** formed between the partially processed CMOS device layer **204** and the III-V device layer **210**, where a high lateral conductivity of the electrically conductive interlayer **228** enables conductive plugs **232** formed to contact a small area of the III-V device that extends beyond the edge of the CMOS device layer **204**. The rest of the III-V device can then be located below the CMOS device layer **204**.

(18) FIG. **3** shows a schematic structure **300** of a semiconductor device **302** integrating CMOS and III-V devices in accordance with a second embodiment. Similar features are labelled with a same

numerical reference. The second embodiment of the semiconductor device **302** as shown in FIG. **3** has a similar structure to that of the semiconductor device **202** as shown in FIG. **2**, except for the removal of the substrate layer **208**.

(19) In the present embodiment, the III-V device **304** of the semiconductor device **302** is an optoelectronic device such as a light-emitting diode (LED). In this case, the active layer **306** of the III-V device **304** formed between the top device electrode layer **308** and the bottom device electrode layer **310** may include an active optical layer comprising a plurality of quantum wells for emitting light. An example of a plurality of quantum wells include multiple alternate layers of (Al)GaN and InGaN layers. In this embodiment, the top device electrode layer **308** includes a p-doped GaN layer such as a Mg-doped GaN layer and the bottom device electrode layer **310** includes a n-doped GaN layer such as a Si-doped GaN layer. The top device electrode layer **308** therefore forms a top device surface and the bottom device electrode layer **310** forms a bottom device surface, where the active optical layer **306** forms an active optical area for the semiconductor device. Although a GaN-based device is used in this embodiment, other III-V semiconductor devices may be used, for example, GaAs-based devices.

(20) In the present embodiment, where the III-V device **304** is an optoelectronic device, the substrate layer **208** has been removed to allow light **312** to be transmitted from the III-V device **304** (e.g. from the active optical area of the III-V device **304**) via the bottom device surface **226** from a bottom side **314** of the semiconductor device **302**. In the present embodiment, a top surface **316** of the semiconductor device **302** wafer is bonded to a support wafer or a supporting structure (not shown) to provide mechanical support for the structure **300**. The support wafer is bonded over a top of the back-end metallization/interconnects (not shown in FIG. **3**) which are formed for electrically connecting the CMOS and III-V devices. In embodiments where chips are made from the structure **300**, a wafer (e.g. 200 mm in diameter) comprising the structure **300** has to be diced up into individual chips (e.g. several mm×several mm). Because these individual chips are much smaller, the support wafer can be thinned down. Further, in embodiments where the chips are mounted onto a holder/PCB, then the rest of the support wafer may be fully removed.

(21) Further, in the present embodiment where the III-V device **304** is an optoelectronic device such as a LED, a higher degree of freedom in designing a layout of the back-end interconnects (not shown in FIG. **3**) is possible since the design of the layout of the back-end interconnects no longer requires to take into consideration issues associated with emission of light for the III-V device **304** (e.g. whether the back-end interconnects may block light emission from the III-V device **304**). In addition, the entire bottom side **314** of the semiconductor device **302** can be used for transmission of light and therefore an effective optical area for the III-V device is increased.

(22) FIG. **4** shows a schematic structure **400** of a semiconductor device **402** integrating CMOS and III-V devices similar to FIG. **3**, but with the substrate layer **208** being replaced by a light transmissible substrate **404** instead of it being removed, in accordance with a third embodiment. As shown in FIG. **4**, the light transmissible substrate **404** is bonded to a bottom device surface **405** of the III-V device **406**, via the buffer layer **212**. In another embodiment where there is no buffer layer **212**, the light transmissible substrate **404** is bonded directly to the bottom device surface **405**. In either case, the light transmissible substrate **404** is considered to be bonded to the bottom device surface **405**.

(23) The light transmissible substrate **404** may include a glass substrate or any other type of optically transparent substrate. In this case, light **408** can be transmitted through the light transmissible substrate **404** at a bottom side **410** of the semiconductor device **402**. In an embodiment where the III-V device **406** is a photodetector, light of any wavelength can directly impinge on the photodetector from the bottom side **410** since the substrate layer **208** of the embodiment of FIG. **2** has been removed. For the embodiment of FIG. **2** where the substrate layer **208** is a silicon substrate, removal of the silicon substrate means photons with energy higher than the silicon band gap energy (~1.1 eV) can be transmitted.

(24) Further in an embodiment where the III-V device **406** is a diode capable of emitting and detecting light, an additional advantage of monolithic integration allows for CMOS circuitry of the CMOS device layer **204** to switch between implementing a driving current through the diode **406** and detecting a current inside the diode **406**. Thus, a diode arrays can function both as detectors and emitters since the CMOS circuitry can be reconfigured for each mode.

(25) The structure **400** as shown in FIG. **4** can be fabricated based on the structure **300** of FIG. **3**. To be clear, as described in relation to FIG. **3**, the structure **300** of FIG. **3** includes the support wafer (not shown) attached to the top surface **316** of the semiconductor device **302**. The support wafer is attached to the top surface **316** to provide mechanical strength for the structure **300** prior to the removal of the substrate **208**. In the present embodiment as shown in FIG. **4**, a starting point for fabricating the structure **400** is therefore a presence of a support wafer attached to a top surface **412** of the structure **400** and an absence of the substrate **208** from the structure **400**. As described above, the light transmissible substrate **404** is then bonded to the bottom device surface **405** of the III-V device **406** to form the structure **400** as shown in FIG. **4**. Once the light transmissible substrate **404** is bonded to the bottom device surface **405**, the support wafer previously attached to the top surface **412** may be removed or may be retained. Similar to the embodiment as shown in FIG. **3**, the device density achievable for the present embodiment as shown in FIG. **4** is also higher than that achieved by the side-by-side configuration as shown in FIG. **1**. Further, similar to the embodiment as shown in FIG. **3**, the present embodiment of FIG. **4** shares similar advantages such as reducing contact resistances to the III-V device **406**, and providing a larger effective optical active area through the bottom side **410** of the semiconductor device **402**.

(26) Although FIGS. **2**, **3** and **4** only show two contacts (e.g. source and drain contacts) of the III-V device **217**, **304**, **406**, it is appreciated that one or more additional contacts (e.g. a gate contact) may be formed for the III-V device **217**, **304**, **406**.

(27) FIG. **5** is a flowchart showing steps of a method **500** for fabricating the semiconductor devices **202**, **302**, **402** of FIGS. **2** to **4**, in accordance with an embodiment. In particular, all the semiconductor devices **202**, **302**, **402** share a similar process steps from a step **502** to a step **512**. However, the fabrication of the semiconductor device **302** of FIG. **3** continues with a step **514**, and the fabrication of the semiconductor device **402** of FIG. **4** continues with the step **514** and a step **516**. The difference between these different embodiments will be made clear in the following description.

(28) In the step **502**, a III-V semiconductor material layer **206** comprising a substrate layer **208** and a device layer **210** attached to the substrate layer **208** is formed. Forming the III-V semiconductor material includes epitaxially depositing the device layer **210** on the substrate layer **208**. The III-V device layer **210** formed is preferably of a high quality with a low particle and defect density. In the present embodiment, the substrate layer **208** comprises a silicon substrate and the III-V semiconductor device layer **210** is GaN-based, where the GaN-based device layer **210** is deposited on the silicon substrate **208** using a metal organic chemical vapor deposition (MOCVD) technique. The III-V semiconductor material layer **206** can therefore be considered as a III-V semiconductor-on-Si substrate in the present embodiment. As discussed in relation to FIGS. **2** to **4**, the device layer **210** includes an active layer **218**, **306** which may either form an electrically active layer or an optically active layer of the III-V device **217**, **304**, **406**. Separately, a CMOS-compatible wafer is sent through a front-end CMOS process. The CMOS-compatible wafer in the present embodiment comprises a silicon (Si) wafer, but it may also include a germanium (Ge) wafer. After the front-end CMOS process, device structures including transistors and isolation regions are formed on a surface of the CMOS-compatible wafer. No major interconnection between the devices on the CMOS-compatible wafer are formed at this stage. A handle wafer is attached to a top side of the CMOS-compatible wafer (i.e. the side of the CMOS-compatible wafer where the device structures are formed) before the CMOS-compatible wafer is etched on a bottom side (i.e. the side of the wafer substrate) to form the partially processed CMOS device layer **204**. In the present

embodiment, the partially processed CMOS device layer **204** is etched to a thickness of less than 1 μm , and preferably to about 800 nm. The handle wafer therefore provides mechanical support for the relatively thin partially processed CMOS device layer **204**. The processes involved in etching the partially processed CMOS device layer **204** are not detailed here for succinctness but the relevant processes are discussed in U.S. Pat. No. 10,049,947 and this is incorporated here in its entirety. The partially processed CMOS device layer **204** includes at least one transistor **205**.

(29) In a step **504**, an electrically conductive interlayer **228** is formed to the device layer **210**. Preferably, the electrically conductive interlayer **228** has an electrical conductivity similar to that of a metal so that a lateral resistance of the electrically conductive interlayer **228** is minimized. The electrically conductive interlayer **228** may therefore include any electrically conductive material so long as the lateral resistance of the electrically conductive interlayer **228** is within an acceptable range (e.g. less than 100 Ohm/sq) so as not to compromise a device performance of the III-V device **217**, **304**, **406**. The electrically conductive interlayer **228** may comprise one or more layers of metals, metallic and/or conductive oxides like indium tin oxide (ITO), in any combination.

(30) In a step **506**, a bonding material **230** is deposited to the electrically conductive interlayer **228**. The bonding material **230** in the present embodiment includes silicon dioxide (SiO_2). In other embodiments, the bonding material **230** may comprise one or more of any other suitable bonding material such as aluminum oxide (AlO_x) and silicon nitride (SiN_x). In some embodiments, the electrically conductive interlayer **228** is bonded directly to the partially processed CMOS device layer **204** without the need of the bonding material **230**. In these cases, the step **506** and its subsequent step **508** are not performed.

(31) In a step **508**, the bonding material **230** is chemo-mechanically polished. This ensures that a flat surface of the bonding material **230** is achieved prior to a subsequent bonding process for enhancing an eventual bonding strength between the electrically conductive interlayer **228** and the partially processed CMOS device layer **204**. In the present embodiment, prior to bonding the partially processed CMOS device layer **204** to the electrically conductive interlayer **228** via the bonding material **230**, the partially processed CMOS device layer **204** is attached to a handle wafer such that the surface of the partially processed CMOS device layer **204** on which the at least one transistor **205** is formed is facing the handle wafer. In the present embodiment, the handle wafer is the same handle wafer as the one previously attached to the partially processed CMOS device layer **204** as described in the step **502** so that no additional step is required to attach the handle wafer at this stage. In an embodiment, a bonding oxide and/or nitride may also be deposited on a bottom side of the partially processed CMOS device layer **204** (i.e. an opposite side to the handle wafer with respect to the partially processed CMOS device layer **204**).

(32) In a step **510**, the electrically conductive interlayer **228** is bonded to the partially processed CMOS device layer **204**. In the present embodiment, the partially processed CMOS device layer **204** is bonded to the electrically conductive interlayer **228** via the bonding material **230**. In an embodiment where another bonding oxide or nitride layer is deposited on the bottom side of the partially processed CMOS device layer **204** as discussed above, this another bonding oxide or nitride layer is bonded to the bonding material **230** deposited on the electrically conductive interlayer **228** so as to bond the partially processed CMOS device layer **204** to the electrically conductive interlayer **228**. In the present embodiment where the partially processed CMOS device layer **204** is attached to the handle substrate prior to this bonding step **510**, the handle substrate is removed after this bonding step **510**. In some embodiments as described above, the electrically conductive interlayer **228** is bonded directly to the partially processed CMOS device layer **204**.

(33) In a step **512**, vias and metal lines/interconnects are formed to electrically connect the at least one transistor **205** of the partially processed CMOS device layer **204** to the III-V device **217**, **304**, **406**. In the present embodiments as shown in FIGS. 2 to 4, contact plugs **232** (e.g. tungsten plugs) are formed on the III-V device contacts such that a top surface of the contact plugs **232** are approximately co-planar with the at least one transistor **205** formed on the partially processed

CMOS device layer **204**. Following this, a back-end CMOS process can commence to form interconnects between the at least one transistor **205** of the partially processed CMOS device layer **204** and the III-V devices **217**, **304**, **406** to form an integrated circuit. For example, the interconnects can be formed on contact pads of the at least one transistor **205** and the contact plugs **232** of the III-V devices to connect these devices. Multiple levels of metals may be used to form a complex network of the interconnects for connecting the III-V devices and the at least one transistor of the CMOS device layer **204**.

(34) The process flow splits here for the semiconductor devices as shown in FIGS. **2** to **4**. The following steps **514** and **516** are directed to embodiments where the III-V device **304**, **406** is an optoelectronic device. For the embodiment of FIG. **2**, the steps **514** and **516** need not be performed.

(35) In the step **514**, the substrate layer **208** is removed. The step **514** is performed after the CMOS device layer **204** is bonded to the electrically conductive interlayer **228** in the step **510**. For the embodiments of FIGS. **3** and **4**, the present step **514** is performed for removing the substrate layer **208** to allow light **312**, **408** to be transmitted and/or received from the bottom side **314**, **410** of the semiconductor device **302**, **402**. Prior to the step **514**, a top side **316**, **412** of the semiconductor device **302**, **402** is attached to a support wafer or structure (not shown) to provide additional structural support given that the substrate layer **208** is removed in these embodiments. The back-end interconnects/pads can be accessed through the support wafer or structure at the top side **316**, **412** of the semiconductor device **302**, **402**, while light is emitted or received from the bottom side **314**, **410** of the semiconductor device **302**, **402**.

(36) The process flow for the semiconductor device **302** as shown in FIG. **3** ends at step **514** where the substrate layer **208** is removed. For the embodiment of FIG. **4**, there is an additional process step to bond the light transmissible substrate **404** to the bottom device surface **405** of the III-V device **406**.

(37) In the step **516**, the light transmissible substrate **404** is bonded to the bottom device surface **405** of the III-V device **406** after the substrate layer **208** is removed in the step **514**, the bottom device surface **405** being a surface previously attached to the substrate layer **208**. The light transmissible substrate **404** is an optically transparent substrate and may include a glass substrate. In the embodiment as shown in FIG. **4**, the bottom device surface **405** is previously attached to the substrate layer **208**, via the buffer layer **212**. In this case, the transmissible substrate **404** is bonded to the bottom device surface **405** of the III-V device **406**, via the buffer layer **212**. In an embodiment where the semiconductor device **402** does not include the buffer layer **212**, the bottom device surface **405** is directly attached to the substrate layer **208**. In this case, the light transmissible substrate **404** is bonded to the bottom device surface **405** of the III-V device **406** directly. In either case, it can be said that the light transmissible substrate **404** is bonded to the bottom device surface **405**, and that the bottom device surface **405** is a surface previously attached to the substrate layer **208**. Optionally, a bonding material such as a bonding oxide or a bonding nitride or a combination of the two can be formed to a bottom side of the III-V device **406** prior to the step **516** to aid in this bonding process step. In an embodiment, another bonding material can also be formed on a surface of the light transmissible substrate **404** prior to the step **516** to enhance a bonding strength of the light transmissible substrate **404** to the bottom device surface **405** of the III-V device **406**. In this case, the light transmissible substrate **404** is bonded to the bottom device surface **405** of the III-V device **406**, via the bonding material formed on the bottom side of the III-V device **406** and the another bonding material formed on the surface of the light transmissible substrate **404**. After performing the step **516**, the support wafer or structure attached to the top side **410** of the semiconductor device **412** may be optionally removed since the light transmissible substrate **404** provides sufficient structural support to the semiconductor device **402**.

(38) FIGS. **6** and **7** demonstrate how a size of a pixel footprint can be reduced by an implementation of the present disclosure, for example, by using the embodiments as shown in FIG. **3** or **4**.

(39) FIG. 6 shows a top plan-view of a circuit layout **600** according to the side-by-side configuration used in the prior art of FIG. 1. In this prior art configuration, CMOS drivers **602** and CMOS control circuitry **604** cannot be placed on top of the pixel as the side-by-side configuration is adopted. In this case, the LED CMOS control circuitry **604** and drivers **602** are placed adjacent to the LED active area **606**, creating a total pixel footprint of about $100\text{ }\mu\text{m}\times 100\text{ }\mu\text{m}$.

(40) FIG. 7 shows a top plan-view of a circuit layout **700** using the embodiments as shown in FIG. 3 or 4 which incorporates an electrically conductive interlayer **228** between the partially processed CMOS device layer **204** and the device layer of the III-V semiconductor material layer. In this embodiment, the III-V device **304**, **406** is an optoelectronic device such as a LED, and the pixel **706** contains the CMOS drivers **702**, the CMOS control circuitry **704** and the LED active area. As shown in FIG. 7, the CMOS control circuitry **704** in the present embodiment can be placed on top of the LED pixel area **706**, thereby decreasing the total pixel area to about $100\text{ }\mu\text{m}\times 70\text{ }\mu\text{m}$ and decreasing the pixel foot-print by about 30%. As is appreciated by the skilled person in the art, the circuit layout **700** as shown in FIG. 7 serves as one embodiment. In another embodiment, the area occupied by the CMOS drivers and the CMOS control circuitry may be similar in size to the active area of the III-V device. In this case, a reduction of the pixel foot-print of close to 50% may be achievable.

(41) FIG. 8 shows a cross-sectional electronic microscopy (EM) image of an actual semiconductor device fabricated, the actual semiconductor device having a similar structure as shown in FIG. 2. As shown in FIG. 8, the integrated semiconductor device **802** comprises a CMOS device layer **804**, a III-V device layer **806** and a substrate layer **808**. In this example, the CMOS device layer **804** is a silicon CMOS device layer, the III-V device layer **806** is a GaN-based layer comprising a GaN LED, and the substrate layer **808** comprises a silicon substrate. The layer **810** represented by a bright line located in-between the silicon CMOS device layer **804** and the III-V device layer **806** is an electrically conductive interlayer **810**. In addition, as shown in FIG. 8, circuit interconnects **812** are formed on the integrated semiconductor device **802** for connecting the silicon CMOS devices of the silicon CMOS device layer **804** with the GaN LED of the III-V device layer **806**. Particularly, FIG. 8 illustrates a placement of the silicon CMOS device layer **804** being placed on top of the GaN LED device so as to achieve the reduced pixel footprint as shown in FIG. 7.

(42) Alternative embodiments of the invention include: (i) a portion of an area (e.g. half of the area) of the III-V device being covered by the partially processed CMOS device layer, while the remaining area of the III-V device being uncovered, and (ii) all contacts (i.e. a source contact, a drain contact and/or a gate contact) of the III-V device may be formed on the top device surface **224**.

(43) For (i) above, although the density of a III-V+CMOS device circuit may not be maximized as compared to an embodiment where the III-V device is located below the partially processed CMOS device layer (e.g. as shown by the embodiment of FIGS. 2, 3 and 4), the density is still enhanced while light extraction is still possible from the top device surface **224**. This trade-off may be reasonable for certain applications.

(44) Although only certain embodiments of the present invention have been described in detail, many variations are possible in accordance with the appended claims. For example, it will be appreciated that certain process steps, like the step **508**, are optional. Further, features described in relation to one embodiment may be incorporated into one or more other embodiments and vice versa.

Claims

1. A method of fabricating a semiconductor device, comprising: (i) forming a III-V semiconductor material layer comprising a substrate layer and a device layer attached to the substrate layer, the device layer having a III-V device comprising a top device electrode layer and a bottom device

- electrode layer and an active layer formed between the top device electrode layer and the bottom device electrode layer; (ii) forming an electrically conductive interlayer on the device layer; (iii) bonding the electrically conductive interlayer to a bottom side of a partially processed CMOS device layer having at least one transistor formed at a top side of the partially processed CMOS device layer; and (iv) forming a contact plug on each of the top device electrode layer and the bottom device electrode layer of the III-V device, wherein a top surface of each of the contact plugs is approximately co-planar with the at least one transistor, and performing a back-end CMOS process to interconnect the at least one transistor and the III-V device to form an integrated circuit.
2. The method according to claim 1, wherein the forming the III-V semiconductor material layer includes epitaxially depositing the device layer on the substrate layer.
 3. The method according to claim 1, wherein the III-V device includes an optoelectronic device having a top device surface, a bottom device surface and an active optical area between the top device and bottom device surfaces; the bottom device surface being attached to the substrate layer and passage of light is via the bottom device surface.
 4. The method according to claim 3, wherein the substrate layer includes a light transmissible substrate.
 5. The method according to claim 3, further comprising removing the substrate layer after the partially processed CMOS device layer is bonded to the electrically conductive interlayer.
 6. The method according to claim 5, further comprising bonding a light transmissible substrate to the bottom device surface of the optoelectronic device after removal of the substrate layer.
 7. The method according to claim 3, further comprising forming vias and metal lines in the back-end CMOS process to electrically connect the at least one transistor of the partially processed CMOS device layer to the optoelectronic device.
 8. The method according to claim 1, further comprising depositing a bonding material on the electrically conductive interlayer prior to bonding the partially processed CMOS device layer to the electrically conductive interlayer, and the method further comprises chemo-mechanically polishing the bonding material.
 9. The method according to claim 1, wherein the electrically conductive interlayer includes indium tin oxide.
 10. A semiconductor device, comprising a partially processed CMOS device layer having at least one transistor formed at a top side of the partially processed CMOS device layer; a III-V semiconductor material layer comprising a substrate layer and a device layer attached to the substrate layer, the device layer having a III-V device, the III-V device comprises a top device electrode layer and a bottom device electrode layer and an active layer formed between the top device electrode layer and the bottom device electrode layer; and an electrically conductive interlayer attached to a bottom side of the partially processed CMOS device layer and sandwiched between the partially processed CMOS device layer and the device layer, wherein a contact plug is formed on each of the top device electrode layer and the bottom device electrode layer of the III-V device, a top surface of each of the contact plugs being approximately co-planar with the at least one transistor, wherein the at least one transistor is interconnected to the III-V device by a back-end CMOS process to form an integrated circuit.
 11. The semiconductor device according to claim 10, wherein the III-V device includes an optoelectronic device having a top device surface, a bottom device surface, and an active optical area between the top device and bottom device surfaces, the bottom device surface being attached to the substrate layer and passage of light is via the bottom device surface.
 12. The semiconductor device according to claim 11, wherein the substrate layer includes a light transmissible substrate.
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