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OPTICAL COUPLING BETWEEN STACKED CHIPS

Abstract

A structure includes a first chip having a first surface and a second chip having a second surface adjacent to the first surface of the first chip. The first chip includes a first optical component and an optical waveguide protrusion adjacent to the first optical component. The optical waveguide protrusion extends above the first surface of the first chip. The second chip includes a second optical component and a groove adjacent to the second optical component. The groove extends from the second surface of the second chip and into a portion of the second chip. The optical waveguide protrusion is positioned in the groove in the second chip.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates generally to semiconductor devices, and more particularly to structures including stacked photonic chips and methods of forming structures including stacked photonic chips.

BACKGROUND

[0002] A photonics chip, also known as an integrated photonics chip or photonic integrated circuit (PIC), is a semiconductor device that integrates various optical components and functions on a single chip or substrate. Photonics chips are finding applications in a wide range of fields, such as telecommunications, data communications, sensing, medical devices, and quantum computing, as they enable faster, more efficient, and higher capacity information processing and communication. As technology continues to advance towards increased functionality, there is a desire to integrate chips or wafers together. This integration, for example, can facilitate the creation of heterogeneous devices or systems, where different types of chips or wafers, including photonic chips or wafers, with specialized functions can be combined.

[0003] From the foregoing discussion, it is desirable to provide improved structures including stacked photonic chips and methods of forming thereof.

SUMMARY

[0004] Embodiments generally relate to semiconductor devices and methods of forming thereof. According to various embodiments, a structure includes a first chip having a first surface, and including a first optical component and an optical waveguide protrusion adjacent to the first optical component. The optical waveguide protrusion extends above the first surface of the first chip. The structure further includes a second chip having a second surface adjacent to the first surface of the first chip. The second chip includes a second optical component and a groove adjacent to the second optical component. The groove may extend from the second surface of the second chip and into a portion of the second chip. The optical waveguide protrusion is positioned in the groove in the second chip.

[0005] According to another aspect, a structure includes a first chip and a second chip stacked over the first chip. The first chip includes a first optical waveguide, a second optical waveguide arranged on the first optical waveguide, and a first dielectric layer surrounding the first optical waveguide. The second optical waveguide extends above a top surface of the first dielectric layer. The second chip includes a second dielectric layer arranged over the first dielectric layer, a third optical waveguide and a groove adjacent to the third optical waveguide in the second dielectric layer. The groove extends from a top surface of the second dielectric layer and into the second dielectric layer. The second optical waveguide is positioned in the groove in the second chip.

[0006] According to various embodiments, a method of forming a structure is provided. The method includes forming a first chip having a first surface and including a first optical component and an optical waveguide protrusion adjacent to the first optical component, the optical waveguide protrusion extending above the first surface of the first chip, forming a second chip having a second surface and including a second optical component and a groove adjacent to the second optical component, the groove extending from the second surface of the second chip and into a portion of the second chip, and positioning the optical waveguide protrusion in the groove in the second chip. The method includes bonding the first surface of the first chip to the second surface of the second chip.

[0007] These and other advantages and features of the embodiments herein disclosed, will become apparent through reference to the following description and the accompanying drawings. Furthermore, it is to be understood that the features of the various embodiments described herein are not mutually exclusive and can exist in various combinations and permutations.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the present invention are described with reference to the following:

[0009] FIGS. **1**A, **2**A, **3**A, **4**A, **5**A, **6**A illustrate cross-sectional views of a first chip or wafer and a second chip or wafer at a fabrication stage of a method for forming a structure in accordance with various embodiments of the invention, and FIGS. **1**B, **2**B, **3**B, **4**B, **5**B, **6**B illustrate cross-sectional view of a structure after stacking and/or bonding the first chip and the second chip of FIGS. **1**A, **2**A, **3**A, **4**A, **5**A, **6**A together, respectively, in accordance with various embodiments of the invention;

[0010] FIG. **1**C illustrates an exemplary top view of the structure of FIG. **1**B, in accordance with various embodiments of the invention;

[0011] FIG. **6**C illustrates an exemplary top view of the structure of FIG. **6**B, in accordance with various embodiments of the invention;

[0012] FIGS. **7**A, **8**A, **9**A illustrate cross-sectional views of another exemplary embodiment of the first chip or wafer and the second chip or wafer prior to stacking and/or bonding, and FIGS. **7**B, **8**B, **9**B illustrate cross-sectional views of another exemplary embodiment of a structure after stacking and/or bonding the first chip and the second chip of FIGS. **7**A, **8**A, **9**A together, respectively, in accordance with various embodiments of the invention;

[0013] FIG. **10** illustrate cross-sectional view of yet another exemplary embodiment of a structure, in accordance with various embodiments of the invention;

[0014] FIG. **11** illustrates a structure having multiple chips bonded together, in accordance with various embodiments of the invention;

[0015] FIGS. **12**A, **13**A, **14**A illustrate cross-sectional views of another exemplary embodiment of the first chip or wafer and the second chip or wafer prior to stacking and/or bonding, and FIGS. **12**B, **13**B, **14**B illustrate cross-sectional views of another exemplary embodiment of a structure after stacking and/or bonding the first chip and the second chip of FIGS. **12**A, **13**A, **14**A together, respectively, in accordance with various embodiments of the invention; and

[0016] FIGS. **15**A-**15**B illustrate another embodiment of a method for forming a structure in accordance with various embodiments of the invention.

DETAILED DESCRIPTION

[0017] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the embodiments. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0018] Aspects of the present invention and certain features, advantages, and details thereof, are explained more fully below with reference to the non-limiting examples illustrated in the accompanying drawings. Descriptions of well-known materials, fabrication tools, processing techniques, etc., are omitted so as not to unnecessarily obscure the invention in detail. It should be understood, however, that the detailed description and the specific examples, while indicating aspects of the invention, are given by way of illustration only, and are not by way of limitation. Various substitutions, modifications, additions, and/or arrangements, within the spirit and/or scope of the underlying inventive concepts will be apparent to those skilled in the art from this disclosure.

[0019] Embodiments generally relate to devices and methods for forming devices. The devices may be, for example, semiconductor devices. For example, the semiconductor devices may be integrated circuits (ICs). Embodiments may be employed to form a three-dimensional (3D) device stack structure, which may be, or include, multiple devices stacked together. The devices of the stack may be the same type of device or a combination of different types of devices, for example, electronic and photonic devices stacked together. The device stack, for example, may be employed for data transfer.

[0020] FIG. **1**A illustrates a cross-sectional view of chip **102** and chip **104** at a fabrication stage of a method for forming a structure in accordance with various embodiments of the invention. The fabrication stage may be prior to stacking and bonding the chip **102** and the chip **104**. The chip **104** is depicted in a flipped orientation. The chips **102** and **104**, for example, may each be part of two different wafers. Alternatively, the chips **102** and **104** may each be individual chips after wafer singulation. In yet other embodiments, one of the chips, for example chip **102**, may be part of a wafer, while the other chip, for example chip **104**, may be an individual chip after wafer singulation, and the chips **102** and **104** may be subsequently bonded together, for example, in a chip-to-wafer bonding process. The chip **102** may have a first surface **112**. The first surface **112**, for example, may be a top surface of the chip **102**. The chip **102** may include an optical waveguide protrusion **124** extending above the first surface **112** of the chip **102**. The optical waveguide protrusion **124** may extend above the first surface **112** by a thickness or height h. For example, the optical waveguide protrusion **124** may have a height h of about 50 nm to about 5000 nm from the first surface **112** of chip **102**. The optical waveguide protrusion **124** may be configured to transfer light in a first direction with respect to the first surface **112** of the chip **102**. The first direction may be away from the chip **102** or towards the chip **102**. For example, the first direction may be a vertical direction with respect to the first surface **112** of the chip **102**.

[0021] In one embodiment, the chip **102** may include an optical component **122** configured to transfer optical signals to or from the optical waveguide protrusion **124**. The optical component **122** may be positioned adjacent to the optical waveguide protrusion **124**. The optical component **122** may be configured to transfer light in a second direction with respect to the first surface **112** of the chip **102**. The second direction may be different from the first direction. In one embodiment, the second direction may be a lateral direction with respect to the first surface **112** of the chip **102**. In one embodiment, the optical component **122** may be an optical waveguide. For example, the optical component **122** may be a first optical waveguide and the optical waveguide protrusion **124** may be a second optical waveguide of the chip **102**. The first optical waveguide, for example, may be a rib waveguide. In one embodiment, the first optical waveguide and the second optical waveguide may be formed of the same material.

[0022] In one embodiment, the optical waveguide protrusion **124** may be disposed on a top surface **141** of the optical component **122**, as illustrated in FIG. **1**A. In other words, the optical waveguide protrusion **124** may be vertically stacked on the optical component **122**. In the case that the optical component **122** is an optical waveguide, the optical waveguide protrusion **124** may overlap a portion of the top surface **141** of the optical component **122** and directly contact the optical component **122**.

[0023] In one embodiment, the chip **102** may include a dielectric layer **105***a*. In some embodiments, the dielectric layer **105***a* may be arranged over a substrate **107***a*, such as a semiconductor substrate. The semiconductor substrate, for example, may be a silicon substrate. In other embodiments, the substrate **107***a* need not be provided. The dielectric layer **105***a* may be formed of a dielectric material having an index of refraction which is lower than the material of the optical component **122** and/or the optical waveguide protrusion **124**. For example, the dielectric layer **105***a* may be formed of a dielectric material such as silicon dioxide. The layer of dielectric material may be planarized to provide the dielectric layer **105***a* with a substantially flat or planar top surface. The top surface of the dielectric layer **105***a*, in one embodiment, may be the first surface **112** of the chip **102**. The dielectric layer **105***a* may surround side surfaces and a bottom surface the optical component **122**. In one embodiment, the top surface of the dielectric layer **105***a* may be substantially coplanar with the top surface **141** of the optical component **122**. In some embodiments, the dielectric layer **105***a* may include metal wiring arranged therein.

[0024] The optical waveguide protrusion **124** may be formed of a homogeneous material (e.g., uniform composition throughout). In one embodiment, the optical waveguide protrusion **124** may be formed of a semiconductor material such as silicon. In another embodiment, the optical waveguide protrusion **124** may be formed of a dielectric material such as silicon nitride. The optical waveguide protrusion **124** may be formed by depositing (e.g., chemical vapor deposition) and patterning its constituent material (e.g., silicon or silicon nitride). For example, the optical waveguide protrusion **124** may be formed by patterning its constituent material using laser ablation. Laser ablation may be used for precision patterning (e.g., material removal) of the optical waveguide protrusion **124** in the nanometer scale. For example, a laser beam, such as from a laser system (e.g., excimer laser), is focused onto the constituent material to cause portions of the material to heat up rapidly. The laser beam may be used to vaporize or blast off a layer of material from the surface irradiated by the laser beam. The depth and precision of material removal may be controlled, for example, by adjusting the laser's power, wavelength, pulse duration, repetition rate, and the focusing optics. For example, the laser beam may have spot size, height×width×length of about 2 nm×20 nm×20 nm. In other embodiments, the optical waveguide protrusion **124** may be formed by patterning its constituent material with lithography and etching (e.g., chemical etching) processes. In some embodiments, the optical waveguide protrusion **124** may be patterned by lithography and etching processes and subsequently patterned by laser ablation. In one embodiment, the optical waveguide protrusion **124** may be formed on the top surface **141** of the optical component **122** and extends to the height, h above the first surface **112** of the chip **102**.

[0025] Now referring to chip **104** which is depicted as inverted in FIGS. **1**A and **1**B, the chip **104** may have a second surface **114**. The chip **104** may include a groove or recess **130** extending below the second surface **114** of the chip **104**. In other words, the groove **130** may extend from the second surface **114** of the chip **104** and into a portion of the chip **104**. The groove **130** may extend from the second surface **114** and partially into the chip **104**, with a depth, d from the second surface **114** of the chip **104**. The depth, d may match the height, h of the optical waveguide protrusion **124**. In some cases, the height, h of the optical waveguide protrusion **124** may be similar to the depth, d of the groove **130** with the height, h of the optical waveguide protrusion **124** having an overetch margin of about 2 nm to about 10 nm to facilitate interlocking with the groove **130**. The groove **130** may be configured to receive the optical waveguide protrusion **124** when the chips **102** and **104** are stacked and/or bonded together with the first surface **112** of the chip **102** facing the second surface **114** of the chip **104**. The groove **130** may correspond to a shape of the optical waveguide protrusion **124**. In one embodiment, the groove **130** may be configured to match a 3D shape of the optical waveguide protrusion **124**. For example, in the case the optical waveguide protrusion **124** has a shape such as cube, cuboid, cylinder, hollow cylinder, rectangular pyramid, or triangular prism, the groove **130** may have a corresponding shape of a cube, cuboid, cylinder, hollow cylinder, rectangular pyramid, or triangular prism in the chip **104**.

[0026] In one embodiment, the chip **104** may further include an optical component **126**. The optical component **126** may be positioned adjacent to the groove **130**. In one embodiment, the optical component **126** may be an optical waveguide (e.g., third optical waveguide). The third optical waveguide, for example, may be a rib waveguide. In one embodiment, the optical component **126** may be formed of the same material as the optical component **122** and the optical waveguide protrusion **124** of the chip **102**. Providing the optical component **122**, the optical waveguide protrusion **124** and the optical component **126** formed of the same material may advantageously facilitate high optical coupling efficiency between the optical component **122** of chip **102** and the optical component **126** of chip **104** when the chips are stacked to form a device stack structure. In one embodiment, the optical component **126** may abut the groove **130**. For example, the groove **130** may expose a side surface of the optical component **126**, as illustrated in FIG. **1**A.

[0027] The chip **104** may include a dielectric layer **105***b*. In some embodiments, the dielectric layer **105***b* may be arranged over a substrate **107***b*, such as a semiconductor substrate. The semiconductor substrate, for example, may be a silicon substrate. In other embodiments, the substrate **107***b* need not be provided. The dielectric layer **105***b* may be formed of a dielectric material having an index of refraction which is lower than the material of the optical component **126** and/or the optical waveguide protrusion **124**. For example, the dielectric layer **105***b* may be formed of a dielectric material such as silicon dioxide. The layer of dielectric material may be planarized to provide the dielectric layer **105***b* with a substantially flat or planar top surface. The top surface of the dielectric layer **105***b* may be the second surface **114** of the chip **104**. In one embodiment, the optical component **126** may be embedded in the dielectric layer **105***b*. As illustrated in FIG. **1**A, the dielectric layer **105***b* may cover a top surface **143** of the optical component **126**. In some embodiments, the dielectric layer **105***b* may include metal wiring arranged therein. In one embodiment, the dielectric layer **105***b* may be a continuous layer formed over the substrate **107***b*. In other embodiments, the dielectric layer **105***b* may be formed in trench opening(s) in the substrate **107***b* and may have a substantially planar top surface with the substrate **107***b* (not shown). For example, the optical component **126** may be embedded in the dielectric layer **105***b* which is formed in a trench opening in the substrate **107***b*.

[0028] In one embodiment, the groove **130** may be formed or dimensioned to fit the optical waveguide protrusion **124**. For example, the groove **130** may precisely fit the optical waveguide protrusion **124**. In one embodiment, the groove **130** may be formed in the dielectric layer **105***b* by using laser ablation. The laser ablation process may be similar to that used for forming the optical waveguide protrusion **124**. In other embodiments, the groove **130** may be formed in the dielectric layer **105***b* by lithography and etching (e.g., chemical etching) processes. In other embodiments, the groove **130** may be patterned by lithography and etching processes and subsequently using laser ablation. The groove **130** may extend from the top surface of the dielectric layer **105***b* to a depth d, which matches the height h of the optical waveguide protrusion **124**.

[0029] The chip **102** may include bond pads **152**, while the chip **104** may include corresponding bond pads **154** for bonding to the bond pads **152** of chip **102**. The bond pads **152** and **154** may be arranged at a predetermined distance from the optical component **122**, optical waveguide protrusion **124** and optical component **126**. The bond pads **152** and **154** may be formed, for example, of a metallic material such as copper.

[0030] In some embodiments, the chips **102** and **104** may each include electronic and/or optical devices. The electronic devices may include active and/or passive components, for example, formed using CMOS processes. For example, the chip **102** may include one or more electronic components arranged on or over the substrate **107***a*. Similarly, the chip **104** may include one or more electronic components arranged on or over the substrate **107***b*. The chip **102** and/or chip **104** may further include optical devices such as, but not limited to, a laser, a modulator, a multiplexer, etc.

[0031] The chips **102** and **104** may be joined together in a face-to-face bonding. In one embodiment, the chip **104** may be stacked over the chip **102**. In another embodiment, the chip **102** may be stacked over the chip **104**. Referring to FIG. **1**B, the chips **102** and **104** may be stacked to form a structure **160** with the second surface **114** of chip **104** being adjacent to the first surface **112** of the chip **102**. The structure **160** may be a device stack. The chips **102** and **104** may be brought together with the first surface **112** of the chip **102** and the second surface **114** of the chip **104** facing each other. For example, one of the chips **102** and **104** may be placed on a stationary plate, while the other chip is aligned and moved towards it to form the structure **160**. The chip **102** and/or chip **104** may be moved to align the optical waveguide protrusion **124** to the groove **130**. The optical waveguide protrusion **124** may be inserted into the groove **130** in the chip **104** so as to interlock with the groove **130**. The optical waveguide protrusion **124** may completely fill a space in the groove **130**. In some embodiments, the optical waveguide protrusion **124** may be used as a dedicated alignment mark in addition to serving as an optical waveguide. The chips **102** and **104**, for example, may be bonded together via wafer bonding processes. In other embodiments, the chips **102** and **104** may be bonded together via chip-to-wafer or chip-to-chip bonding processes. The first surface **112** of chip **102** may be bonded to the second surface **114** of chip **104** at a bonding interface **165**. The second surface **114** of the chip **104** may directly contact the first surface **112** of the chip **102** at the bonding interface **165**. The chips **102** and **104** may be bonded together by dielectric bonding or hybrid bonding. For example, in the dielectric bonding process, a low temperature anneal may be performed at a sufficient temperature and for a sufficient duration to establish a face-to-face bond between contacting surfaces of the dielectric layer **105***a* of the chip **102** and the dielectric layer **105***b* of the chip **104**. In the hybrid bonding process, metal-metal bonds (e.g., Cu—Cu bonds) may be formed between the bond pads **152** of chip **102** and the corresponding bond pads **154** of chip **104**, and dielectric-dielectric bonds (e.g., oxide-oxide bonds) may be formed between the dielectric layer **105***a* of chip **102** and the dielectric layer **105***b* of chip **104**. For example, standard thermocompressive bonding tools and techniques may be used.

[0032] Accordingly, the optical waveguide protrusion **124** of chip **102** is positioned in the groove **130** in the chip **104** of the device stack. The dielectric layer **105***b* of the chip **104** may surround the optical waveguide protrusion **124** when the optical waveguide protrusion **124** is positioned in the groove **130**. The optical component **122**, the optical waveguide protrusion **124** and the optical component **126** may be optically coupled to each other. The optical waveguide protrusion **124** may be configured to couple and transmit optical signals from the optical component **122** of the chip **102** to the optical component **126** of the chip **104**, or from the optical component **126** of the chip **104** to the optical component **122** of the chip **102**. In one embodiment, the optical component **126** is arranged laterally adjacent to the optical waveguide protrusion **124** such that the optical waveguide protrusion **124** may laterally couple optical signals to a side surface of the optical component **126**. In one embodiment, the optical waveguide protrusion **124** may abut a side surface of the optical component **126**, as illustrated in FIG. **1**B.

[0033] In the case that the optical component **126** is an optical waveguide, in one embodiment, the optical waveguide protrusion **124** may be bonded to the optical component **126** and to the dielectric layer **105***b* of the chip **104** in a second bonding process. In one embodiment, the second bonding process may employ laser ablation. For example, laser ablation may be used to melt and fuse the optical waveguide protrusion **124** and the optical component **126** together at the abutting side surfaces, and the optical waveguide protrusion **124** and the dielectric layer **105***b* of the chip **104** at the abutting surfaces. Bonding the optical waveguide protrusion **124** to the optical component **126** may minimize optical losses.

[0034] FIG. **1**C illustrates an exemplary top view of the structure **160** after bonding the chips **102** and **104** together, in accordance with various embodiments of the invention. The optical waveguide protrusion **124** directly contacts the optical component **126** in the chip **104** and overlaps and directly contacts the optical component **122** in the chip **102**. Accordingly, the optical waveguide protrusion **124** may transfer optical signals from chip **102** to chip **104** or from chip **104** to chip with minimal or reduced optical loss.

[0035] Accordingly, optical signals may be coupled efficiently between optical waveguides in different chips or wafers of the device stack structure through the optical waveguide protrusion. The optical waveguide protrusion according to various embodiments may advantageously facilitate optical transmission between chips, or wafers, or chip-to-wafer with reduced loss of optical signals. Further, the optical waveguide protrusion may facilitate forming a 3D device stack structure using different chips/wafers.

[0036] FIGS. **2**A-**2**B illustrate another embodiment of a method for forming a structure in accordance with various embodiments of the invention. In FIGS. **2**A-**2**B, like numerals refer to like elements of FIGS. **1**A-**1**B. The method is similar to those described in FIGS. **1**A-**1**B, but in this case, for chip **204**, which is similarly depicted as inverted in FIGS. **2**A and **2**B, the groove **130** is positioned over the optical component **126** in the chip **204**. The groove **130** may expose a portion of the top surface **143** of the optical component **126**. FIG. **2**B illustrates a cross-sectional view of a structure **260** after stacking and/or bonding the chips **102** and **204** together, in accordance with various embodiments of the invention.

[0037] The chips **102** and **204** may be brought together with the first surface **112** of the chip **102** and the second surface **114** of the chip **204** facing each other. The chip **102** and/or chip **204** may be moved to align the optical waveguide protrusion **124** to the groove **130**. The optical waveguide protrusion **124** may be inserted into the groove **130** in the chip **104** so as to interlock with the groove **130**. The chips **102** and **204** may be bonded in the same manner as chips **102** and **104** as described with respect to FIG. **1**B. In one embodiment, the optical component **126** is arranged over the optical waveguide protrusion **124** in the structure **160** such that the optical waveguide protrusion **124** may vertically couple optical signals to the top surface **143** of the optical component **126**. The optical component **126** overlaps the optical waveguide protrusion **124** in the structure **160**. In one embodiment, a top surface **145** of the optical waveguide protrusion **124** abuts a portion of the top surface **143** of the optical component **126** as shown in FIG. **2**B. Similar to chips **102** and **104** in FIG. **1**B, in the case that the optical component **126** is an optical waveguide, the optical waveguide protrusion **124** of chip **102** may be bonded to the optical component **126** and to the dielectric layer **105***b* of the chip **204** in a second bonding process. For example, laser ablation may be used to melt and fuse the optical waveguide protrusion **124** and the optical component **126** together at the abutting top surfaces, and the optical waveguide protrusion **124** and the dielectric layer **105***b* of the chip **204** at the abutting surfaces.

[0038] FIGS. **3**A-**3**B illustrate cross-sectional views of chips **302** and **304**, in which like numerals refer to like elements of the previous figures. The chip **304** is depicted as inverted in FIGS. **3**A and **3**B. In one embodiment, the optical waveguide protrusion **124** of chip **302** has a right triangle cross-section and the groove **130** of chip **304** has a corresponding right triangle cross-section. For example, the optical waveguide protrusion **124** and the groove **130** may have the shape of a right angle prism. Referring to FIG. **3**A, the optical waveguide protrusion **124** may include a side surface **145***a* which extends at a right angle with respect to the first surface **112** of the chip **302**, and an adjoining side surface **145***b* which is slanted with respect to the first surface **112** of the chip **302**. The side surface **145***b* may adjoin the side surface **145***a* to form a corner of the optical waveguide protrusion **124** having an acute angle. FIG. **3**B illustrates a cross-sectional view of a structure **360** after stacking and/or bonding the chips **302** and **304** together, in accordance with various embodiments of the invention. The chip **302** and/or chip **304** may be moved to align the optical waveguide protrusion **124** to the groove **130**. The optical waveguide protrusion **124** may be inserted into the groove **130** in the chip **304** so as to interlock with the groove **130**. The optical waveguide protrusion **124** may fill a space in the groove **130**. The top surface of the dielectric layer **105***a* may directly contact the top surface of the dielectric layer **105***b*. The chips **302** and **304** may be bonded in the same manner as chips **102** and **104** as described with respect to FIG. **1**B.

[0039] In one embodiment, the side surface **145***a* of the optical waveguide protrusion **124** may abut a side surface of the optical component **126** as shown in FIG. **3**B. The dielectric layer **105***b* of the chip **304** may surround the optical waveguide protrusion **124** and abut the side surface **145***b* and a portion of the side surface **145***a* of the optical waveguide protrusion **124**. Similar to chips **102** and **104** in FIG. **1**B, in the case that the optical component **126** is an optical waveguide, the optical waveguide protrusion **124** of chip **302** may be bonded to the optical component **126** and to the dielectric layer **105***b* of the chip **304** in a second bonding process. For example, laser ablation may be used to melt and fuse the optical waveguide protrusion **124** and the optical component **126** together at the abutting side surfaces, and the optical waveguide protrusion **124** and the dielectric layer **105***b* of the chip **304** at the abutting surfaces.

[0040] FIGS. **4**A-**4**B illustrate cross-sectional views of chips **402** and **404**, in which like numerals refer to like elements of the previous figures. The chip **404** is depicted as inverted in FIGS. **4**A and **4**B. In one embodiment, the optical waveguide protrusion **124** of chip **402** has a side surface **145***a* which may be slanted at a first angle with respect to the first surface **112** of chip **402** and an adjoining side surface **145***b* which may be slanted at a second angle with respect to the first surface **112** of the chip **402**, as illustrated in FIG. **4**A. The first angle and the second angle may be acute angles. In some embodiments, the second angle may be different from the first angle. In other embodiments, the first angle and the second angle may be the same. The side surface **145***a* may adjoin the side surface **145***b* to form a first corner of the optical waveguide protrusion **124** having an acute angle. The side surface **145***a* may adjoin a bottom surface **145***c* of the optical waveguide protrusion **124** to form a second corner of the optical waveguide protrusion **124** having an obtuse angle. The side surface **145***b* may adjoin the bottom surface **145***c* to form a third corner of the optical waveguide protrusion **124** having an acute angle. For example, the optical waveguide protrusion **124** may be formed by depositing one or more layers of its constituent material (e.g., silicon or silicon nitride) and patterning using laser ablation to form the side surfaces **145***a*, **145***b* and the first corner having the acute angle. The chip **404** may have the groove **130** with a corner having the corresponding acute angle to the first corner of the optical waveguide protrusion **124**. In one embodiment, the optical component **126** may be an optical waveguide (e.g., third optical waveguide) and may include an extension portion **126***a*. For example, the extension portion **126***a* of the third optical waveguide may extend laterally from the side surface of the third optical waveguide and vertically to the second surface **114** of the chip **404**. The extension portion **126***a* of the third optical waveguide may have a side surface **441***a* which may be slanted at a third angle with respect to the second surface **114** of chip **404**. The third angle of the side surface **441***a* may correspond to the first angle of the side surface **145***a* of the optical waveguide protrusion **124** and may be the same. For example, groove **130** and extension portion **126***a* of the third optical waveguide may be formed by forming a cavity in the dielectric layer **105***b* of chip **404**, the cavity may abut and expose a side surface of the third optical waveguide, filling the cavity with constituent material of the extension portion **126***a* of the optical waveguide, performing a planarization process to form a substantially planar top surface of the dielectric layer **105***b* and the material of the extension portion **126***a*, and subsequently patterning the dielectric layer **105***b* and the material of the extension portion **126***a* using laser ablation to form groove **130** and the extension portion **126***a* with the side surface **441***a*. The groove **130** may expose the side surface **441***a* of the extension portion **126***a* of the third optical waveguide, as illustrated in FIG. **4**A.
[0041] FIG. **4**B illustrates a cross-sectional view of a structure **460** after stacking and/or bonding the chips **402** and **404** together, in accordance with various embodiments of the invention. The chip **402** and/or chip **404** may be moved to align the optical waveguide protrusion **124** to the groove **130**. For example, the alignment may include vertical and horizontal movements of the chip **402** and/or chip **404** so as to insert the optical waveguide protrusion **124** into the groove **130** in the chip **404**. The optical waveguide protrusion **124** may be inserted into the groove **130** in the chip **404** so as to interlock with the groove **130**. The side surface **145***a* of the optical waveguide protrusion **124** may abut the side surface **441***a* of the extension portion **126***a* of the third optical waveguide as shown in FIG. **4**B. The extension portion **126***a* may improve optical coupling between the optical waveguide protrusion **124** and the third optical waveguide. The chips **402** and **404** may be bonded in the same manner as chips **102** and **104** as described with respect to FIG. **1**B. The optical waveguide protrusion **124** of chip **402** may be bonded to the extension portion **126***a* of the third optical waveguide and to the dielectric layer **105***b* of the chip **404** in a second bonding process similar to that described with respect to chips **102** and **104** in FIG. **1**B.
[0042] FIGS. **5**A-**5**B illustrate cross-sectional views of chips **502** and **504**, in which like numerals refer to like elements of the previous figures. The chip **504** is depicted as inverted in FIGS. **5**A and **5**B. In one embodiment, the optical waveguide protrusion **124** of chip **502** has a side surface **145***a*

which may be slanted at a first angle with respect to the first surface **112** of the chip **502**, and an adjoining side surface **145***b* which may be slanted at a second angle with respect to the first surface **112** of the chip **502**, as illustrated in FIG. **5**A. The first angle may be an obtuse angle while the second angle may be an acute angle. The side surface **145***a* may adjoin the side surface **145***b* to form a corner of the optical waveguide protrusion **124** having an obtuse angle of the optical waveguide protrusion **124** above the first surface **112** of the chip **502**. For example, the optical waveguide protrusion **124** may be formed by depositing one or more layers of its constituent material (e.g., silicon or silicon nitride) and patterning using laser ablation to form the side surfaces **145***a*, **145***b* and the corner having the obtuse angle. The chip **504** may have the groove **130** with a corner having the corresponding obtuse angle. For example, the optical waveguide protrusion **124** may have the shape of a triangular prism. In one embodiment, the optical component **126** may be an optical waveguide (e.g., third optical waveguide) and may include an extension portion **126***a*. For example, the extension portion **126***a* of the third optical waveguide may extend laterally from the side surface of the third optical waveguide and vertically to the second surface **114** of the chip **504**. The extension portion **126***a* of the third optical waveguide may have a side surface **441***a* which may be slanted at a third angle with respect to the second surface **114** of chip **504**. The third angle of the side surface **441***a* may correspond to the first angle of the side surface **145***a* of the optical waveguide protrusion **124** and may be the same. The groove **130** and extension portion **126***a* of the third optical waveguide of chip **504** may be formed in a similar manner as that described with respect to the groove **130** and extension portion **126***a* of the third optical waveguide of chip **404** in FIG. **4**A. The groove **130** may expose the side surface **441***a* of the extension portion **126***a* of the third optical waveguide.

[0043] FIG. **5**B illustrates a cross-sectional view of a structure **560** after stacking and/or bonding the chips **502** and **504** together, in accordance with various embodiments of the invention. The chip **502** and/or chip **504** may be moved to align the optical waveguide protrusion **124** to the groove **130**. The optical waveguide protrusion **124** may be positioned in the groove **130** in the chip **504** so as to interlock with the groove **130**. The side surface **145***a* of the second optical waveguide **124** may abut the side surface **441***a* of the extension portion **126***a* of the third optical waveguide. The extension portion **126***a* may improve optical coupling between the optical waveguide protrusion **124** and the third optical waveguide. The chips **502** and **504** may be bonded in the same manner as chips **102** and **104** as described with respect to FIG. **1**B. The optical waveguide protrusion **124** of chip **502** may be bonded to the extension portion **126***a* of the third optical waveguide and to the dielectric layer **105***b* of the chip **504** in a second bonding process similar to that described with respect to chips **102** and **104** in FIG. **1**B.

[0044] FIGS. **6**A-**6**B illustrate side views of chips **602** and **604**, in which like numerals refer to like elements of the previous figures. The chip **604** is depicted as inverted in FIGS. **6**A and **6**B. In one embodiment, the optical waveguide protrusion **124**, which extends above the first surface **112** of the chip **602**, may be an upper portion of a second optical waveguide, and the second optical waveguide may further include a lower portion **124***a* extending below the first surface **112** of the chip **602** and into a portion of the chip **602**. The second optical waveguide may be an annular waveguide having concentric inner and outer ring-shaped edges **643***b* and **643***a*, as illustrated in FIG. **6**A and FIG. **6**C. The second optical waveguide may have a closed loop configuration. The second optical waveguide forms a ring resonator. For example, the ring resonator may be configured to transfer and/or filter light of a predetermined frequency or range of frequencies. The groove **130** has a corresponding ring-shaped configuration which matches the ring-shaped configuration of the optical waveguide protrusion **124** (e.g., the upper portion of the second optical waveguide). In one embodiment, the optical component **122** of chip **602** may be a first optical waveguide, while the optical component **126** of chip **604** may be a third optical waveguide. The lower portion **124***a* of the second optical waveguide may be laterally spaced from the first optical waveguide in the chip **602** (shown as dotted lines in FIGS. **6**A and **6**B). The lower portion **124***a* of the second optical waveguide may be separated from the first optical waveguide by dielectric material of the dielectric layer **105***a* of chip **602** (not shown in FIG. **6**A). The groove **130** may be separated from the third optical waveguide by dielectric material of the dielectric layer **105***b* of chip **604** (not shown in FIG. **6**A).

[0045] FIG. **6**B illustrates a cross-sectional view of a structure **660** after stacking and/or bonding the chips **602** and **604** together, in accordance with various embodiments of the invention. The chip **602** and/or chip **604** may be moved to align the optical waveguide protrusion **124**, which in this case has an annular configuration, to the groove **130**. The optical waveguide protrusion **124** may be inserted into the groove **130** in the chip **604** so as to interlock with the groove **130**. The chips **602** and **604** may be bonded in the same manner as chips **102** and **104** as described with respect to FIG. **1**B. The optical waveguide protrusion **124** of chip **602** (e.g., the upper portion of the second optical waveguide may be bonded to the dielectric layer **105***b* of the chip **604** in a second bonding process. For example, laser ablation may be used to melt and fuse the optical waveguide protrusion **124** and the dielectric layer **105***b* of the chip **604** at surfaces where the optical waveguide protrusion **124** contacts the dielectric layer **105***b*.

[0046] FIG. **6**C illustrates an exemplary top view of the structure **660** after stacking and/or bonding the chips **602** and **604** together, in accordance with various embodiments of the invention. As shown, the optical waveguide protrusion **124** (e.g., upper portion of the second optical waveguide) may be spaced apart from the optical component **122** (e.g., the first optical waveguide) and the optical component **126** (e.g., the third optical waveguide). For example, the second optical waveguide may be laterally spaced from the first optical waveguide and from the third optical waveguide. In other words, the second optical waveguide does not physically contact the first optical waveguide and the third optical waveguide. The first optical waveguide, the second optical waveguide which forms the ring resonator and the third optical waveguide may be optically coupled to each other. As described, the ring resonator may be configured to transfer light of a predetermined frequency or range of frequencies. One of the first optical waveguide and the third optical waveguide may be an input bus, while the other may be an output bus.

[0047] In other embodiments, the structure may include a sealing material between the optical waveguide protrusion **124** and the groove **130**. In one embodiment, the sealing material may be formed on the optical waveguide protrusion **124** prior to bonding the chips together. FIGS. **7**A-**7**B illustrate cross-sectional views of chips **802** and **804**, in which like numerals refer to like elements of the previous figures. The chip **804** is depicted as inverted in FIGS. **7**A and **7**B. Referring to FIG. **7**A, chip **802** may include the optical waveguide protrusion **124** extending above the first surface **112** of chip **802**, and a sealing material **810** lining a surface of the optical waveguide protrusion **124**. The sealing material **810**, for example, may have a liquid composition and may be cured to harden with light or temperature. In some embodiments, the sealing material **810** may be applied on a die-to-die basis. In other embodiments, the sealing material **810** may be coated or filled in the groove **130** of chip **804**, for example, prior to stacking the wafers together. When the wafers are stacked together, the sealing material **810** may fill the imperfections or surface roughness of the optical waveguide protrusion **124** and the groove **130**. The sealing material **810** may form a sealant having thickness of about 2 nm to about 100 nm depending on the vertical/lateral roughness of the optical waveguide protrusion **124** and the groove **130**. The sealant may fill a gap between the surfaces of the optical waveguide protrusion **124** and the groove **130**. In some cases, sufficient overetch of the groove **130** matching the vertical/lateral roughness may be performed so as to allow for interlocking of the optical waveguide protrusion **124** and the groove **130**.

[0048] Referring to FIG. **7**B, the optical waveguide protrusion **124** may be positioned in the groove **130** when the chips **802** and **804** are stacked and/or bonded together. The sealing material **810** may fill imperfections between the opposing surfaces of the optical waveguide protrusion **124** and the optical component **126**/extension portion of the third optical waveguide and between the opposing surfaces of the optical waveguide protrusion **124** and the dielectric layer **105***b*. Accordingly, the sealing material **810** may improve light coupling between the optical waveguide protrusion **124** and the optical component **126**. The sealing material **810** may have a lower melting temperature than the material of the optical waveguides, and an index of refraction which is similar to the optical waveguides. The sealing material **810** may facilitate connection between the optical waveguide protrusion **124** and the third optical waveguide. In one embodiment, the sealing material **810** may be a bonding glue.

[0049] In one embodiment, the structure may include a reflective surface along a side of the groove **130**. The optical waveguide protrusion **124** may interface the reflective surface when then chips are stacked and/or bonded together. FIGS. **8**A-**8**B illustrate cross-sectional views of chips **902** and **904**, in which like numerals refer to like elements of the previous figures. The chip **904** is depicted as inverted in FIGS. **8**A and **8**B. Referring to FIG. **8**A, a reflective material **920** may be arranged along a side of the groove **130** in chip **904**. The groove **130** may expose a reflective surface of the reflective material **920**. In one embodiment, the reflective material **920** may be formed, for example, of metal or silicide. In one embodiment, the groove **130** and the reflective surface may be formed by forming a rectangular cavity in the chip **904**, filling the cavity with a metallic material, and etching the metallic material using laser ablation (e.g., a subtractive manufacturing process) to form the groove **130**, with the remaining metallic material serving as the reflective material **920** along a side of the groove **130**. In another embodiment, the reflective material **920** may be formed, for example, by a silicidation process after the groove **130** is formed. As described, in some embodiments, the dielectric layer **105***b* may be formed in trench opening(s) in the substrate **107***b* and the dielectric layer **105***b* may have a substantially planar top surface with the substrate **107***b* (not shown). The optical component **126** may be embedded in the dielectric layer **105***b* which is formed in a trench opening in the substrate **107***b*. In such cases, the groove **130**, may be formed to extend from a top surface of the substrate **107***b* and into a portion of the substrate **107***b* (not shown), with the groove **130** exposing a side surface of the optical component **126**. The reflective material **920** may be then formed along a side of the groove **130** by a silicidation process. Referring to FIG. **8**B, the structure **960** may include the optical waveguide protrusion **124** positioned in the groove **130** when the chips **902** and **904** are stacked and/or bonded together. The optical waveguide protrusion **124** positioned in the groove **130** may interface with the reflective surface of the reflective material **920**. The reflective surface may be provided to reflect light traveling in the optical waveguide protrusion **124** to the optical component **126**, reducing optical loss and improving light coupling between the optical waveguide protrusion **124** and the optical component **126**.

[0050] In one embodiment, the structure may include a cavity arranged below the optical waveguide protrusion **124**. FIGS. **9**A-**9**B illustrate cross-sectional views of chips **1002** and **1004**, in which like numerals refer to like elements of the previous figures. The chip **1004** is depicted as inverted in FIGS. **9**A and **9**B. Referring to FIG. **9**A, chip **1002** may include the optical waveguide protrusion **124** extending above the first surface **112** of the chip **1002**. A cavity **1030** may be formed below the optical waveguide protrusion **124**. For example, laser ablation may be used to remove a portion of material of the optical waveguide protrusion **124** to form the cavity **1030**. In the case that the optical component **122** is an optical waveguide, a portion of material of the optical component **122** may be removed to form the cavity **1030** below the optical waveguide protrusion **124**. For example, to remove material beneath the first surface **112** of chip **1002**, the laser ablation process may use two or multi-photon absorption (e.g., two or more light sources are focused at a point and scanned to remove material three dimensionally) for the light to penetrate deep and be absorbed within the bulk of the material. In this way, when the light is absorbed, the material can be removed not only from the surface but also beneath. The optical waveguide protrusion **124** may overhang the cavity **1030**. Referring to FIG. **9**B, the structure **1060** may include the optical waveguide protrusion **124** positioned in the groove **130** when the chips **1002** and **1004** are stacked and/or bonded together. The optical waveguide protrusion **124** may partially fill the groove **130**.

The cavity **1030** may be enclosed, for example, by the optical component **122**, the optical waveguide protrusion **124**, and dielectric layers **105***a* and **105** of the chips **1002** and **1004**, respectively, forming an air gap **1030***a* below the optical waveguide protrusion **124**. The air gap **1030***a* may be provided to minimize reflection and optical losses.

[0051] FIG. **10** illustrates a structure **1160** with chips **1102** and **1104** bonded together. The structure **1160** may include the optical waveguide protrusion **124** interfacing the reflective surface of the reflective material **920** similar to the structure **960** described with respect to FIG. **8**B, and the air gap **1030***a* arranged below the optical waveguide protrusion **124** similar to the structure **1060** described with respect to FIG. **9**B.

[0052] FIG. **11** illustrates a structure **1260** having multiple chips bonded together. In one embodiment, the structure **1260** may include stacked chips **1102**, **1104** and **1106**. For example, chip **1104** may be an intermediate chip positioned between chip **1102** and chip **1106**. The chip **1102** may have first surface **112** and may include the optical component **122** and the optical waveguide protrusion **124** extending above the first surface **112** of the chip **1102**. The chip **1104** may have second surface **114** and third surface **1116**, and may include groove **130**, optical component **126**, and optical component **1128**. The groove **130** may extend from the second surface **114** and into a portion of the chip **1104**. The optical waveguide protrusion **124** of chip **1102** may be positioned in the groove **130** in the chip **1104**. The second surface **114** of the chip **1104** may face the first surface **112** of the chip **1102** when the chips **1102** and **1104** are stacked. The chip **1104** may be bonded to the chip **1102** at the bonding interface **165**. In some embodiments, the chip **1104** may further include an optical waveguide protrusion **1125** extending above the third surface **1116** of the chip **1104**. The optical component **126** and the optical component **1128** may optically couple the optical waveguide protrusion **124** positioned in the groove **130** and the optical waveguide protrusion **1125** extending above the third surface **1116** of the chip **1104**. The chip **1106** may have fourth surface **1118** and may include groove **1135** and optical component **1129**. The groove **1135** may extend from the fourth surface **1118** and into a portion of the chip **1106**. The optical waveguide protrusion **1125** of chip **1104** may be positioned in the groove **1135** in the chip **1106**. The chips **1102**, **1104** and/or **1106** may include metal wiring. For example, the chip **1104** may be an intermediate chip positioned between chip **1102** and chip **1106**, and may include optical components and metal wiring.

[0053] FIGS. **12**A-**12**B illustrate another embodiment of a method for forming a structure in accordance with various embodiments of the invention. In FIGS. **12**A-**12**B, like numerals refer to like elements of the previous figures. For example, the method is similar to those described in FIGS. **1**A-**1**B and FIGS. **3**A-**3**B, but in this case, chip **1302** may include a groove **1330** in addition to the optical waveguide protrusion **124** while chip **1304** may include an optical waveguide protrusion **1324** in addition to the groove **130**. The groove **1330** may extend below the first surface **112** of the chip **1302**. The groove **1330** may be configured to receive the optical waveguide protrusion **1324** disposed on chip **1304** when the chips **1302** and **1304** are stacked and/or or bonded together with the first surface **112** of the chip **1302** facing the second surface **114** of the chip **1304**. The groove **1330** may correspond to a shape of the optical waveguide protrusion **1324**. The optical waveguide protrusion **1324** may extend above the second surface **114** of the chip **1304**. The chip **1302** may further include optical component **1322** adjacent to the groove **1330**. In one embodiment, the optical component **122** and the optical component **1322** may each be optical waveguides which are disposed in different layers or levels of the chip **1302**. The chip **1304** may further include optical component **1326** adjacent to the optical waveguide protrusion **1324**. In one embodiment, the optical component **126** and the optical component **1326** may each be optical waveguides which are disposed in different layers or levels of the chip **1304**. FIG. **12**B illustrates a cross-sectional view of a structure **1360** after stacking and/or bonding the chips **1302** and **1304** together, in accordance with various embodiments of the invention. As illustrated, the optical waveguide protrusion **124** is positioned in the groove **130** in the chip **1304**, and the optical waveguide protrusion **1324** is positioned in the groove **1330** in the chip **1302**.

[0054] FIGS. **13**A-**13**B illustrate cross-sectional views of chips **1402** and **1404**, in which like numerals refer to like elements of the previous figures. In the case the optical component **122** and the optical component **126** are optical waveguides (e.g., first optical waveguide and third optical waveguide, respectively) and the optical waveguide protrusion **124** is a second optical waveguide formed on the top surface of the first optical waveguide, in one embodiment, the optical waveguide protrusion **124** of chip **1402** may include a waveguide extension portion **124***b* which may extend laterally beyond a side surface of the first optical waveguide. In one embodiment, the waveguide extension portion **124***b* may be configured to contact a portion of the top surface **143** of the third optical waveguide when the chips **1402** and **1404** are stacked and/or bonded. The waveguide extension portion **124***b*, for example, may extend laterally from a lower portion of the side surface **145***a* of the optical waveguide protrusion **124**, as illustrated in FIG. **13**A. In one embodiment, the waveguide extension portion **124***b* may include a top surface adjoining a side surface to form a corner having an acute angle. For example, the waveguide extension portion **124***b* may have a triangular shape with the corner having the acute angle extending laterally from the side surface **145***a*. The optical waveguide protrusion **124** with the waveguide extension portion **124***b* may be configured to abut the third optical waveguide when the chips **1402** and **1404** are stacked with an upper portion of the side surface **145***a* of the optical waveguide protrusion **124** contacting a side surface of the third optical waveguide and the waveguide extension portion **124***b* contacting a portion of the top surface **143** of the third optical waveguide. In one embodiment, the optical waveguide protrusion **124** and the waveguide extension portion **124***b* may be formed by depositing the constituent material of the optical waveguide protrusion **124** and the waveguide extension portion **124***b*, patterning the material into a rectangular shape and subsequently using laser ablation to form the final shapes of the optical waveguide protrusion **124** with the waveguide extension portion **124***b* (e.g., triangular shapes of the optical waveguide protrusion **124** and the waveguide extension portion **124***b* of chip **1402** illustrated in FIG. **13**A), for example, in the same step from the original rectangular shape. The groove **130** of the chip **1404** may be configured to receive the optical waveguide protrusion **124** with the waveguide extension portion **124***b* of the chip **1402**. The groove **130** may accommodate the optical waveguide protrusion **124** and the waveguide extension portion **124***b* when the chips **1402** and **1404** are stacked and/or bonded.

[0055] FIG. **13**B illustrates a cross-sectional view of a structure **1460** after stacking and/or bonding the chips **1402** and **1404** together, in accordance with various embodiments of the invention. The chip **1402** and/or chip **1404** may be moved to align the optical waveguide protrusion **124** with the waveguide extension portion **124***b* to the groove **130**. For example, the alignment may include a vertical movement, or vertical and horizontal movements of the chip **1402** and/or chip **1404** so as to insert the optical waveguide protrusion **124** with the waveguide extension portion **124***b* into the groove **130** in the chip **404**. The optical waveguide protrusion **124** with the waveguide extension portion **124***b* may be inserted into the groove **130** in the chip **1404** so as to interlock with the groove **130**. The optical waveguide protrusion **124** and the waveguide extension portion **124***b* may abut the optical component **126**. As shown in FIG. **13**B, the optical waveguide protrusion **124** may abut a side surface of the third optical waveguide, and the waveguide extension portion **124***b* may abut a portion of the top surface **143** of the third optical waveguide. The waveguide extension portion **124***b* may minimize reflections and facilitate improved light coupling. The waveguide extension portion **124***b* may extend laterally beyond a side surface of the first optical waveguide (optical component **122**) for improved forward coupling of light by the optical waveguide protrusion **124** to the third optical waveguide (optical component **126**). Providing the waveguide extension portion **124***b* may further minimize insertion loss in the device stack structure. In one embodiment, an air gap **1450** may be formed below the waveguide extension portion **124***b* when the optical waveguide protrusion **124** with the waveguide extension portion **124***b* is positioned in the groove **130**. As illustrated in FIG. **13**B, the air gap **1450** may be formed along a sidewall of the waveguide extension portion **124***b* when the optical waveguide protrusion **124** with the waveguide extension portion **124***b* is positioned in the groove **130**. The air gap **1450**, for example, may be defined by the waveguide extension portion **124***b*, a dielectric layer of chip **1402** and a dielectric layer of chip **1404**. The air gap **1450** may further minimize reflection and optical losses.

[0056] FIGS. **14**A-**14**B illustrate another embodiment of a method for forming a structure in accordance with various embodiments of the invention. In FIGS. **14**A-**14**B, like numerals refer to like elements of the previous figures. For example, the method is similar to those described in FIGS. **1**A-**1**B, but in this case, an alignment structure may be formed on one of the chips which will be stacked and/or bonded together, for example chip **1502**, while a second groove corresponding to a shape of the alignment structure may be formed in the other one of the chips, for example chip **1504**. For example, alignment structure **1550** may be formed on chip **1502**, and a second groove **1552** corresponding to the alignment structure **1550** may be formed in chip **1504**, which is depicted as inverted in FIGS. **14**A and **14**B. The alignment structure **1550** may extend above first surface **112** of the chip **1502**. The alignment structure **1550**, for example, may have a shape such as cube, cuboid, cylinder, hollow cylinder, 3D spiral or any other basic 3D polygons. The alignment structure **1550** may be a topography alignment structure and need not serve any electrical function and/or optical function. The second groove **1552** may extend below the second surface **114** of the chip **1504**. The second groove **1552** may be configured to receive the alignment structure **1550** when the chips **1502** and **1504** are stacked and/or or bonded together with the first surface **112** of the chip **1502** facing the second surface **114** of the chip **1504**. The second groove **1552** may correspond to a shape of the alignment structure **1550**. The alignment structure **1550** may be formed of metallic, dielectric or semiconductor material. In one embodiment, the alignment structure **1550** may be formed of the same material as the optical waveguide protrusion **124**. In some cases, the alignment structure **1550** may facilitate the interlocking of the two chips **1502** and **1504** (allow for self-assembly) by energy minimization of the surface or interface between the two chips **1502** and **1504**, which promotes capillary action for covalent bonding between the surfaces. The alignment structure **1550** may be formed, for example, in the same step as the optical waveguide protrusion **124**, such as patterned using laser ablation. The alignment structure **1550** may be formed by depositing its constituent material and patterning, for example, using laser ablation with the same or similar process condition for forming the optical waveguide protrusion **124**. FIG. **14**B illustrates a cross-sectional view of a structure **1560** after stacking and/or bonding the chips **1502** and **1504** together, in accordance with various embodiments of the invention. As illustrated, the alignment structure **1550** may be positioned in the second groove **1552** in the chip **1504**. The alignment structure **1550** may facilitate translational (e.g., x-direction, y-direction) and/or rotational alignment between chips **1502** and **1504**. Accordingly, the alignment structure **1550** may have better resolution than conventional wafer alignment tools. The alignment structure **1550** may be formed such that it is located nearer to the optical devices of the device stack structure for better alignment.

[0057] As described, the optical waveguide protrusion **124** may be employed for optically coupling two or more chips vertically stacked together in a device stack, such as in a chip-to-chip bonding process, in a wafer-to-wafer bonding process or chip-to-wafer bonding process. FIGS. **15**A-**15**B illustrate an embodiment of a chip-to-wafer bonding process for forming a structure in accordance with various embodiments of the invention. In FIGS. **15**A-**15**B, like numerals refer to like elements of the previous figures. For example, the method is similar to those described in FIGS. **1**A-**1**B, but in this case, chips **1604***a* and **1604***b* which are depicted as inverted in FIGS. **15**A and **15**B may be provided for stacking and/or bonding to wafer **1602**. For example, optical waveguide protrusions may be formed on the wafer **1602**, while grooves corresponding to the optical waveguide protrusions may be formed in the chips **1604***a* and **1604***b*. Alternatively, optical waveguide protrusions may be formed on the chips **1604***a* and **1604***b*, while grooves corresponding to the optical waveguide protrusions may be formed in the wafer **1602**. In yet other embodiments, an optical waveguide protrusion may be formed on the wafer **1602** for interlocking with a groove on

one of the chips **1604***a* and **1604***b*, and a groove may be formed in the wafer **1602** for interlocking with an optical waveguide protrusion on the other one of the chips **1604***a* and **1604***b*. For purpose of illustration, wafer **1602** may be provided with optical waveguide protrusions **124** and **1624** extending above the first surface **112** of wafer **1602** for interlocking with groove **130** of chip **1604***a* and groove **1630** of chip **1604***b*, respectively. The groove **130** may extend below the second surface **114***a* of chip **1604***a* and correspond to the shape of optical waveguide protrusion **124**. The groove **1630** may extend below the second surface **114***b* of chip **1604***b* and correspond to the shape of optical waveguide protrusion **1624**. The wafer **1602** may further include optical component **122** adjacent to the optical waveguide protrusion **124**, and optical component **1622** adjacent to the optical waveguide protrusion **1624**. The chip **1604***a* may further include optical component **126** adjacent to the groove **130**. The chip **1604***b* may further include optical component **1626** adjacent to the groove **1630**. The optical components **122** and **126** and may be configured to transfer optical signals to or from the optical waveguide protrusion **124**, while the optical components **1622** and **1626** may be configured to transfer optical signals to or from the optical waveguide protrusion **1624**. In one embodiment, the optical components **122**, **126**, **1622** and **1626** may be optical waveguides. The optical waveguide protrusion **124** and **1624** and the optical components **122**, **126**, **1622** and **1626** may be formed of the same material. FIG. **16**B illustrates a cross-sectional view of a structure **1660** after stacking and/or bonding the wafer **1602** and the chips **1604***a* and **1604***b* together, in accordance with various embodiments of the invention.
[0058] The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments, therefore, are to be considered in all respects illustrative rather than limiting the invention described herein. Scope of the invention is thus indicated by the appended claims, rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are intended to be embraced therein.

Claims

1. A structure comprising: a first chip having a first surface, and including a first optical component and an optical waveguide protrusion adjacent to the first optical component, the optical waveguide protrusion extending above the first surface of the first chip; and a second chip having a second surface adjacent to the first surface of the first chip, the second chip including a second optical component and a groove adjacent to the second optical component, the groove extending from the second surface of the second chip and into a portion of the second chip, wherein the optical waveguide protrusion is positioned in the groove in the second chip.
2. The structure of claim 1, wherein the first optical component is a first optical waveguide and the optical waveguide protrusion is a second optical waveguide of the structure, the second optical waveguide is disposed on the first optical waveguide and abuts a portion of a top surface of the first optical waveguide.
3. The structure of claim 2, wherein the second optical component is a third optical waveguide of the structure, the third optical waveguide abuts the second optical waveguide.
4. The structure of claim 3, wherein the third optical waveguide is arranged laterally adjacent to the second optical waveguide.
5. The structure of claim 3, wherein the third optical waveguide is arranged over the second optical waveguide and a portion of the third optical waveguide overlaps the second optical waveguide.
6. The structure of claim 1, wherein the first optical component is a first optical waveguide and the optical waveguide protrusion is an upper portion of a second optical waveguide, the second optical waveguide further comprises a lower portion extending below the first surface of the first chip, the second optical waveguide is laterally spaced from the first optical waveguide in the first chip, and the second optical waveguide forms a ring resonator.

7. The structure of claim 1, wherein the first chip further includes a first dielectric layer surrounding the first optical component, and the second chip further includes a second dielectric layer surrounding the groove, wherein the second dielectric layer directly contacts the first dielectric layer.
8. The structure of claim 7, wherein a top surface of the first dielectric layer and the first optical component is substantially coplanar, and the second dielectric layer directly contacts at least a portion of the top surface of the first optical component.
9. The structure of claim 1, wherein the first chip further comprises a first bond pad, and the second chip further comprises a second bond pad, the first chip is bonded to the second chip via the first bond pad and the second bond pad.
10. The structure of claim 1, wherein the first optical component and the second optical component are optical waveguides, and the first optical component, the second optical component and the optical waveguide protrusion are formed of the same material.
11. The structure of claim 1, wherein the optical waveguide protrusion partially fills the groove, and further comprising an air gap below the optical waveguide protrusion.
12. The structure of claim 1, further comprising a sealing material between the optical waveguide protrusion and the groove.
13. The structure of claim 1, further comprising a reflective surface along a side of the groove, wherein optical waveguide protrusion interfaces with the reflective surface.
14. The structure of claim 1, wherein the first chip further includes a second groove extending below the first surface of the first chip, and the second chip further includes a second optical waveguide protrusion extending above the second surface of the second chip, and wherein the second optical waveguide protrusion is positioned in the second groove in the first chip.
15. The structure of claim 1, wherein the first chip further comprises an alignment structure extending above the first surface of the first chip, the second chip having a second groove extending below the second surface of the second chip, and wherein the alignment structure is positioned in the second groove in the second chip.
16. A structure comprising: a first chip including a first optical waveguide, a second optical waveguide arranged on the first optical waveguide, and a first dielectric layer surrounding the first optical waveguide, wherein the second optical waveguide extends above a top surface of the first dielectric layer; and a second chip stacked over the first chip, the second chip including a second dielectric layer arranged over the first dielectric layer, a third optical waveguide and a groove adjacent to the third optical waveguide in the second dielectric layer, wherein the groove extends from a top surface of the second dielectric layer and into the second dielectric layer, wherein the second optical waveguide is positioned in the groove in the second chip.
17. The structure of claim 16, wherein the second optical waveguide abuts the first optical waveguide and the third optical waveguide.
18. The structure of claim 17, wherein the second optical waveguide has a first side surface adjoining a second side surface to form a corner of the second optical waveguide having an acute angle.
19. A method, comprising: forming a first chip having a first surface, and including a first optical component and an optical waveguide protrusion adjacent to the first optical component, the optical waveguide protrusion extending above the first surface of the first chip; forming a second chip having a second surface and including a second optical component and a groove adjacent to the second optical component, the groove extending from the second surface of the second chip and into a portion of the second chip; positioning the optical waveguide protrusion in the groove in the second chip; and bonding the first surface of the first chip to the second surface of the second chip.
20. The method of claim 19, wherein forming the first chip further comprises patterning the optical waveguide protrusion using laser ablation.