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3D IC comprising semiconductor substrates with different bandgaps

Abstract

Various embodiments of the present disclosure are directed towards a three-dimensional (3D) IC comprising semiconductor substrates with different bandgaps. The 3D IC chip comprises a first IC chip and a second IC chip overlying and bonded to the first IC chip. The first IC chip comprises a first semiconductor substrate with a first bandgap, and further comprises and a first device on and partially formed by the first semiconductor substrate. The second IC chip comprises a second semiconductor substrate with a second bandgap different than the first bandgap, and further comprises a second device on the second semiconductor substrate.

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Background/Summary

REFERENCE TO RELATED APPLICATION (1) This application claims the benefit of U.S. Provisional Application No. 63/329,544, filed on Apr. 11, 2022, the contents of which are incorporated by reference in their entirety.

BACKGROUND

(1) Semiconductor devices based on silicon have been the standard for the past few decades. However, semiconductor devices based on gallium nitride (GaN) and the like are increasingly used for power supply/converter applications and radio frequency (RF) applications. Compared to silicon-based semiconductor devices, semiconductor devices based on GaN and the like have wide bandgaps. Among other things, the wide bandgaps enable operation at high frequencies, high voltages, and high temperatures.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
- (2) FIG. 1 illustrates a cross-sectional view of some embodiments of a three-dimensional (3D) integrated circuit (IC) comprising semiconductor substrates with different bandgaps.
- (3) FIGS. 2A-2H illustrate cross-sectional views of some alternative embodiments of the 3D IC of FIG. 1 in which IC chips of the 3D IC are varied.
- (4) FIG. 3 illustrates a cross-sectional view of some more detailed embodiments of the 3D IC of FIG. 1 in which devices of the 3D IC have additional detail.
- (5) FIGS. 4A and 4B illustrate circuit diagrams respectively of some different embodiments of the 3D IC of FIG. 3.
- (6) FIGS. 5A-5C illustrate cross-sectional views of some alternative embodiments of the 3D IC of FIG. 3.
- (7) FIG. 6 illustrates a cross-sectional view of some more detailed embodiments of the 3D IC of FIG. 3 in which interconnect structures of the 3D IC have additional detail.
- (8) FIGS. 7A-7C illustrate cross-sectional views of some alternative embodiments of the 3D IC of FIG. 6.
- (9) FIG. 8 illustrates a cross-sectional view of some alternative embodiments of the 3D IC of FIG. 1 in which the 3D IC comprises additional IC chips.
- (10) FIGS. 9A-9H illustrate cross-sectional views of some alternative embodiments of the 3D IC of FIG. 8 in which orientations of IC chips of the 3D IC are varied.
- (11) FIG. 10 illustrates a cross-sectional view of some embodiments of the 3D IC of FIG. 8 in which the 3D IC has additional detail.
- (12) FIG. 11 illustrates a cross-sectional view of some embodiments of the 3D IC of FIG. 1 in which devices of the 3D IC correspond to radio frequency (RF).
- (13) FIG. 12 illustrates a circuit diagram of some embodiments of the 3D IC of FIG. 11.
- (14) FIGS. 13A and 13B illustrate some embodiments respectively of IC chips of the 3D IC of FIGS. 11 and 12 in which components of the 3D IC are split amongst the IC chips.
- (15) FIG. 14 illustrates a schematic view of some embodiments of the 3D IC of FIGS. 13A and 13B in which a second IC chip is overlaid on a first IC chip.
- (16) FIG. 15 illustrates a cross-sectional view of some embodiments of the 3D IC of FIG. 11 in which the 3D IC has additional detail.
- (17) FIGS. 16A-16C illustrate cross-sectional views of some alternative embodiments of the 3D IC of FIG. 15 in which IC chips of the 3D IC have different orientations.
- (18) FIG. 17 illustrates a cross-sectional view of some alternative embodiments of the 3D IC of FIG. 11 in which the 3D IC further comprises an antenna.
- (19) FIG. 18 illustrates a perspective view of some embodiments of the antenna of FIG. 17.

- (20) FIG. 19 illustrates a circuit diagram of some embodiments of the 3D IC of FIG. 17.
- (21) FIG. 20 illustrates a cross-sectional view of some embodiments of the 3D IC of FIG. 17 in which the 3D IC has additional detail.
- (22) FIG. 21 illustrates a cross-sectional view of some alternative embodiments of the 3D IC of FIG. 11 in which the 3D IC further comprises a mixer and a local oscillator.
- (23) FIG. 22 illustrates a circuit diagram of some embodiments of the 3D IC of FIG. 21.
- (24) FIG. 23 illustrates a cross-sectional view of some embodiments of the 3D IC of FIG. 21 in which the 3D IC has additional detail.
- (25) FIGS. 24-26 illustrate a series of cross-sectional views of some embodiments of a method for forming a 3D IC comprising semiconductor substrates with different bandgaps.
- (26) FIG. 27 illustrates a block diagram of some embodiments of the method of FIGS. 24-26.
- (27) FIG. 28 illustrates a cross-sectional view of some embodiments of an additional processing step that may be performed as part of the method of FIGS. 24-26.
- (28) FIGS. 29-31 illustrate a series of cross-sectional views of some alternative embodiments of the method of FIGS. 24-26 in which devices of the 3D IC correspond to RF.

DETAILED DESCRIPTION

- (29) The present disclosure provides many different embodiments, or examples, for implementing different features of this disclosure. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.
- (30) Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.
- (31) Compared to silicon-based counterparts, gallium nitride (GaN) devices may have smaller resistance-capacitance (RC) parasitic elements, which allow the GaN devices to operate at high frequencies. Accordingly, GaN devices find application in radio frequency (RF). For example, GaN devices may find application within monolithic microwave integrated circuits (MMICs) used for fifth generation (5G) wireless communication.
- (32) An MMIC may be formed by forming both passive and active devices on a GaN substrate. However, forming the active and passive devices using GaN may be more costly than forming the active and passive devices using silicon. Further, there may be little to no performance advantage to forming the passive devices using GaN compared to silicon. Accordingly, costs may be overly high. An MMIC may alternatively be formed by forming the active devices on a GaN substrate, and by forming the passive devices on a silicon substrate. The passive and active devices may then be packaged together so as to laterally electrically couple the passive and active devices together. However, this increases the wire length between the passive and active devices, which enlarges RC parasitic elements. Accordingly, RF performance may be poor, especially for high operating frequencies.
- (33) In addition to high operating frequencies, GaN devices may have high operating temperatures and high operating voltages compared to silicon counterparts. Accordingly, GaN devices find

application within power supplies and/or power converters. As an example, GaN devices may find application within analog-to-digital converters (ADC), digital-to-analog converters (DAC), power supplies for computer servers, and so on.

(34) Such a computer server power supply may comprise a full-bridge converter integrated circuit (IC) chip and a logical link control (LLC) converter IC chip. The two IC chips may be bonded to a printed circuit board (PCB) and electrically coupled together through the PCB and/or wire bonds. Further, the full-bridge converter IC chip may comprise GaN devices on a first GaN substrate, and the LLC IC chip may comprise GaN device on a second GaN substrate. However, use of two separate IC chips may increase size and may further increase cost (e.g., from electrically coupling the two IC chips together). Further, use of two separate IC chips increases wire length between the GaN devices, which increases parasitic inductance and capacitance and hence degrades performance. Further yet, the full-bridge converter IC chip and/or the LLC IC chip may comprise devices for which GaN provides little to no benefit. As such, costs may be overly high from forming these devices using GaN.

(35) Various embodiments of the present disclosure are directed towards a three-dimensional (3D) IC comprising semiconductor substrates with different bandgaps. The 3D IC chip comprises a first IC chip and a second IC chip overlying and bonded to the first IC chip. The first IC chip comprises a first semiconductor substrate with a first bandgap, and further comprises a first device on the first semiconductor substrate. In some embodiments, the first device is formed in part by the first semiconductor substrate, whereby the first device may also be referred to as a first semiconductor device. The second IC chip comprises a second semiconductor substrate with a second bandgap different than the first bandgap, and further comprises a second device on the second semiconductor substrate. In some embodiments, the second device is formed in part by the second semiconductor substrate, whereby the second device may also be referred to as a second semiconductor device.

(36) The 3D IC chip may, for example, find application with power applications and RF applications in at least some embodiments in which the first and second semiconductor substrates correspond to GaN and silicon. For example, components of an RF circuit (e.g., a transceiver, a front-end module (FEM), an MMIC, and so on) or components of a power circuit (e.g., a full-bridge converter, an LLC converter, and so on) may be split amongst the first and second IC chips and interconnect by interconnect structures of the IC chips. Devices that benefit from the wide bandgap of GaN (e.g., the first device) may be formed on the first semiconductor substrate, whereas devices that don't benefit or minimally benefit from the wide bandgap of GaN (e.g., the second device) may be formed at reduced cost on the second semiconductor substrate.

(37) Additionally, because the first and second IC chips are vertically stacked, wire length between the first and second IC chips is small and area consumed by the 3D IC is small. The small wire lengths may lead to reduced parasitic inductance and capacitance and may hence lead to enhanced performance. The small area may allow enhanced functional density on a PCB or other substrate to which the 3D IC is mounted and may hence allow reduced costs.

(38) With reference to FIG. 1, a cross-sectional view **100** of some embodiments of a 3D IC comprising a first semiconductor substrate **102** and a second semiconductor substrate **104** is provided in which the first and second semiconductor substrates **102**, **104** have different bandgaps. For example, the first semiconductor substrate **102** may have a larger or wider bandgap than the second semiconductor substrate **104** or vice versa.

(39) The first semiconductor substrate **102** is part of a first IC chip **106**, which comprises a first active device **108**, a first frontside interconnect structure **110**, and a support substrate **112**. The support substrate **112** is on a backside **102bs** of the first semiconductor substrate **102**, and the first active device **108** and the first frontside interconnect structure **110** are on a frontside **102fs** of the first semiconductor substrate **102** opposite the backside **102bs**. In alternative embodiments, the support substrate **112** is omitted from the 3D IC. Further, the first active device **108** is between the

first semiconductor substrate **102** and the first frontside interconnect structure **110** and is partially formed by the first semiconductor substrate **102**. As such, the first active device **108** may also be referred to as a first semiconductor device.

(40) The second semiconductor substrate **104** is part of a second IC chip **114**, which overlies and is bonded to the first IC chip **106**. The second IC chip **114** comprises a plurality of second active devices **116**, a plurality of passive devices **118**, and a second frontside interconnect structure **120** on a frontside **104fs** of the second semiconductor substrate **104**, opposite a backside **104bs** of the second semiconductor substrate **104**. The second active devices **116** are between the second semiconductor substrate **104** and the second frontside interconnect structure **120** and are partially formed by the second semiconductor substrate **104**. As such, the second active devices **116** may also be referred to as second semiconductor devices. Further, the passive devices **118** are in the second frontside interconnect structure **120**. In alternative embodiments, one, some, or all of the passive devices **118** is/are in the first frontside interconnect structure **110**.

(41) In some embodiments, the first semiconductor substrate **102** has a larger bandgap than the second semiconductor substrate **104**. For example, the first semiconductor substrate **102** may be or comprise GaN or the like, whereas the second semiconductor substrate **104** may be or comprise monocrystalline silicon or the like. In at least some of such embodiments, the 3D IC chip may find application with power applications and RF applications. For example, the 3D IC may be or otherwise comprise a transceiver, a FEM, an MMIC, or some other suitable RF device. As another, the 3D IC may be or otherwise comprise a full-bridge power converter, an LLC power converter, or some other suitable power device.

(42) To the extent that the first semiconductor substrate **102** has a larger bandgap than the second semiconductor substrate **104**, active devices that benefit from the larger bandgap (e.g., the first active device **108**) are on and partially formed by the first semiconductor substrate **102**. Active devices used for power supplies, power conversion, RF switching, RF amplification, and so on tend to benefit from the larger bandgap because the larger bandgap enables operation at higher frequencies, higher voltages, and higher temperatures. Further, active devices that don't benefit or minimally benefit from the larger bandgap of the first semiconductor substrate **102** (e.g., the second active devices **116**) may be formed on the second semiconductor substrate **104**. At least when the second semiconductor substrate **104** is or comprises monocrystalline silicon, this may reduce costs because forming active devices on non-silicon substrates tends to be more costly than forming active devices on silicon substrates.

(43) Additionally, because the first and second IC chips **106**, **114** are vertically stacked, wire length between the first and second IC chips **106**, **114** is small and area consumed by the 3D IC is small. The small wire lengths may lead to reduced parasitic inductance and capacitance and may hence enhance performance. For example, compared to wire bonding the first and second IC chips **106**, **114** together when laterally bordering, parasitic inductance may be reduced from 3.2 nanohenries to 0.4 nanohenries for an 88% reduction. Other suitable values are, however, amenable. The small area may allow enhanced functional density on a PCB or other substrate to which the 3D IC is mounted and may hence reduce costs.

(44) With continued reference to FIG. **1**, the first and second IC chips **106**, **114** are vertically stacked and bonded together frontside to frontside at a bond interface **122**. By frontside to frontside, it is meant that first and second IC chips **106**, **114** are bonded together at the bond interface **122** so the frontside **102fs** of the first semiconductor substrate **102** and the frontside **104fs** of the second semiconductor substrate **104** face each other. The bonding both physical secures the first and second IC chips **106**, **114** to each other and electrically couples the first and second IC chips **106**, **114** to each other.

(45) The first and second frontside interconnect structures **110**, **120** define conductive paths electrically coupling the first and second active devices **108**, **116** and the passive devices **118** together to form a circuit. The circuit may, for example, be a full-bridge power converter, an LLC

power converter, a transceiver, a FEM, an MMIC, or the like. As seen hereafter, the first and second frontside interconnect structures **110**, **120** may comprise stacks of conductive features (not shown) embedded in corresponding dielectric layers (not shown). The conductive features define the conductive paths and may, for example, comprise vias, contacts, wires, pads, other suitable types of conductive features, or any combination of the foregoing.

(46) In some embodiments, the first semiconductor substrate **102** is or comprises GaN or some other suitable group III-V semiconductor material. In some embodiments, the first semiconductor substrate **102** comprises a GaN layer and an aluminum gallium nitride (AlGaN) layer overlying and directly contacting the GaN layer at a heterojunction. In some embodiments, the first semiconductor substrate **102** has a bandgap greater than a bandgap of silicon and/or greater than a bandgap of the second semiconductor substrate **104**. In some embodiments, the first semiconductor substrate **102** has a bandgap greater than about 1.5 electron volts, about 2 electron volts, about 2.5 electron volts, or some other suitable value.

(47) In some embodiments, the support substrate **112** is or comprises monocrystalline silicon, silicon carbide, sapphire, or some other suitable semiconductor material. In some embodiments, the first semiconductor substrate **102** and the support substrate **112** form a composite substrate. For example, to the extent that the first semiconductor substrate **102** is or comprises GaN and the support substrate **112** is monocrystalline silicon, silicon carbide, or sapphire, the composite substrate may be or comprise a GaN on silicon substrate, a GaN on silicon carbide substrate, or a GaN on sapphire substrate. In some embodiments, the support substrate **112** is or comprises a same semiconductor material as the second semiconductor substrate **104** and/or has a lesser bandgap than the first semiconductor substrate **102**.

(48) In some embodiments, the support substrate **112** has a high resistance to reduce substrate losses for RF applications and the like. The high resistance may, for example, be greater than about 1 kilo-ohms/centimeter ($\text{k}\Omega/\text{cm}$), about $1.8\text{ k}\Omega/\text{cm}$, or about $3\text{ k}\Omega/\text{cm}$, and/or may, for example, be about $1\text{--}1.8\text{ k}\Omega/\text{cm}$ or about $1.8\text{--}3\text{ k}\Omega/\text{cm}$. In other embodiments, the support substrate **112** has a low resistance less than about $30\text{ }\Omega/\text{cm}$, about $20\text{ }\Omega/\text{cm}$, or about $10\text{ }\Omega/\text{cm}$. In yet other embodiments, the support substrate **112** has a resistance that is about $100\text{--}500\text{ }\Omega/\text{cm}$, about $100\text{--}300\text{ }\Omega/\text{cm}$, or about $300\text{--}500\text{ }\Omega/\text{cm}$. Notwithstanding the foregoing resistance values, other suitable values are amenable in alternative embodiments.

(49) In some embodiments, the second semiconductor substrate **104** is or comprises monocrystalline silicon or some other semiconductor material. In some embodiments, the second semiconductor substrate **104** has a lesser bandgap than the first semiconductor substrate **102**. In some embodiments, the second semiconductor substrate **104** has a bandgap within about 0.5, 0.4, 0.2, or 0.1 electron volts of a bandgap of silicon and/or has a bandgap of about 0.5-1.5 electron volts. Alternative bandgaps are, however, amenable.

(50) In some embodiments, the first semiconductor substrate **102** is or comprises GaN, the second semiconductor substrate **104** is or comprises monocrystalline silicon, the support substrate **112** is or comprises monocrystalline silicon, the first active device **108** is a high-electron-mobility transistor (HEMT), and the second active devices **116** are metal-oxide-semiconductor field-effect transistors (MOSFETs). Different material types and/or device types are, however, amenable in alternative embodiments.

(51) In some embodiments, the first active device **108** is a HEMT, a MOSFET, or some other suitable type of active device. In some embodiments, the second active devices **116** are MOSFETs or some other suitable type of active device. The MOSFETs may, for example, be a fin field-effect transistors (finFETs), gate-all-around field-effect transistors (GAA FETs), nanosheet field-effect transistors, some other suitable type of MOSFET, or any combination of the foregoing. In some embodiments, the second active devices **116** correspond to complementary metal-oxide semiconductor (CMOS) semiconductor devices and hence correspond to an n-type MOSFET and a p-type MOSFET. In some embodiments, the passive devices **118** are or comprise capacitors,

resistors, inductors, transformers, some other suitable type of passive device, or any combination of the foregoing.

(52) As noted above, the first and second active devices **108**, **116** and the passive devices **118** together to form a circuit. In some embodiments, the first active device **108** corresponds to an analog portion of the circuit, whereas the second active devices **116** correspond to a digital portion of the circuit. Further, in some embodiments, the first active device **108** corresponds to power supply and/or conversion portions of the circuit, whereas the second active devices **116** correspond to logic or control portions of the circuit.

(53) With reference to FIGS. 2A-2H, cross-sectional views **200A-200H** of some alternative embodiments of the 3D IC of FIG. 1 are provided in which the first and second IC chips **106**, **114** of the 3D IC are varied.

(54) As illustrated by the cross-sectional view **200A** of FIG. 2A, the first IC chip **106** is vertically flipped, such that the first and second IC chips **106**, **114** are bonded together backside to frontside at the bond interface **122**. As a result, the first IC chip **106** further comprises a backside interconnect structure **202** and a through substrate vias (TSV) **204**.

(55) The backside interconnect structure **202** overlies the first semiconductor substrate **102** and the support substrate **112** on the backside **102bs** of the first semiconductor substrate **102**, and the TSV **204** extends through the first semiconductor substrate **102** and the support substrate **112** from the backside interconnect structure **202** to the first frontside interconnect structure **110**. The backside interconnect structure **202** defines a conductive path electrically coupling the TSV **204** to the second frontside interconnect structure **120**, and the TSV **204** defines a conductive path electrically coupling the backside interconnect structure **202** to the first frontside interconnect structure **110**. As seen hereafter, the backside interconnect structure **202** may comprise a stack of conductive features (not shown) embedded in a corresponding dielectric layer (not shown). The conductive features define conductive paths and may, for example, comprise vias, wires, pads, redistribution layers (RDLs), and so on.

(56) As illustrated by the cross-sectional view **200B** of FIG. 2B, the second IC chip **114** is vertically flipped, such that the first and second IC chips **106**, **114** are bonded together frontside to backside at the bond interface **122**. As a result, the second IC chip **114** further comprises a backside interconnect structure **206** and a TSV **208**.

(57) The backside interconnect structure **206** underlies the second semiconductor substrate **104** on the backside **104bs** of the second semiconductor substrate **104**, and the TSV **208** extends through the second semiconductor substrate **104** from the backside interconnect structure **206** to the second frontside interconnect structure **120**. The backside interconnect structure **206** defines a conductive path electrically coupling the TSV **208** to the first frontside interconnect structure **110**, and the TSV **208** defines a conductive path electrically coupling the backside interconnect structure **206** to the second frontside interconnect structure **120**. As seen hereafter, the backside interconnect structure **206** may comprise a stack of conductive features (not shown) embedded in a corresponding dielectric layer (not shown). The conductive features define conductive paths and may, for example, comprise vias, wires, pads, RDLs, and so on.

(58) As illustrated by the cross-sectional view **200C** of FIG. 2C, the first and second IC chips **106**, **114** are each vertically flipped, such that the first and second IC chips **106**, **114** are bonded together backside to backside at the bond interface **122**. The first IC chip **106** is as in FIG. 2A, whereas the second IC chip **114** is as in FIG. 2B.

(59) As illustrated by the cross-sectional view **200D** of FIG. 2D, the support substrate **112** is omitted. Omitting the support substrate **112** may, for example, reduce RF substrate loss and/or enhance thermal dissipation.

(60) As illustrated by the cross-sectional view **200E** of FIG. 2E, the passive devices **118** are in the first frontside interconnect structure **110** instead of the second frontside interconnect structure **120**.

(61) As illustrated by the cross-sectional view **200F** of FIG. 2F, the passive devices **118** are split

amongst the first and second frontside interconnect structures **110**, **120**.

(62) As illustrated by the cross-sectional view **200G** of FIG. 2G, the second IC chip **114** is vertically flipped, such that the first and second IC chips **106**, **114** are bonded together frontside to backside at the bond interface **122**. As a result, the second IC chip **114** is as illustrated and described with regard to FIG. 2B, except that the second IC chip **114** is devoid of the backside interconnect structure **206**. Such embodiments may, for example, arise when the second semiconductor substrate **104** is transferred to the first IC chip **106** or is otherwise deposited directly on the first IC chip **106** during manufacture of the 3D IC.

(63) As illustrated by the cross-sectional view **200H** of FIG. 2H, the first and second IC chips **106**, **114** are each vertically flipped, such that the first and second IC chips **106**, **114** are bonded together backside to backside at the bond interface **122**. As a result, the first and second IC chips **106**, **114** are as illustrated and described with regard to FIG. 2C, except that the second IC chip **114** is devoid of the backside interconnect structure **206**. Such embodiments may, for example, arise when the second semiconductor substrate **104** is transferred to the first IC chip **106** or is otherwise deposited directly on the first IC chip **106** during manufacture of the 3D IC.

(64) While FIGS. 2A-2H illustrate modifications to the 3D IC in FIG. 1, the modifications are also applicable to the 3D IC in any of FIGS. 2A-2H. As an example, which is exemplified by FIG. 2D, the support substrate **112** may be omitted in any of FIGS. 2A-2C and 2E-2H. As another example, which is exemplified by FIG. 2E, the passive devices **118** may be in the first frontside interconnect structure **110** in any of FIGS. 2A-2D, 2G, and 2H. As yet another example, which is exemplified by FIG. 2F, the passive devices **118** may be split amongst the first and second frontside interconnect structures **110**, **120** in any of FIGS. 2A-2D, 2G, and 2H.

(65) With reference to FIG. 3, a cross-sectional view **300** of some more detailed embodiments of the 3D IC of FIG. 1 is provided in which the first and second active devices **108**, **116** and the passive devices **118** have additional detail. Additionally, the first semiconductor substrate **102** has additional detail.

(66) The first semiconductor substrate **102** overlies the support substrate **112** and is or comprises a heterojunction structure. Further, the heterojunction structure comprises a channel layer **302** and a barrier layer **304**. The channel layer **302** and the barrier layer **304** are semiconductor layers having unequal bandgaps and are or comprise group III-V semiconductor materials, group II-VI semiconductor materials, or the like.

(67) The channel layer **302** underlies and directly contacts the barrier layer **304** at a heterojunction. Further, the channel layer **302** optionally accommodates a two-dimensional carrier gas **306**. For example, the channel layer **302** may accommodate a two-dimensional electron gas or a two-dimensional hole gas. The barrier layer **304** is polarized to promote formation of the two-dimensional carrier gas **306**. The polarization may, for example, result from spontaneous polarization effects and/or piezoelectric polarization effects.

(68) In some embodiments, the channel layer **302** is or comprises GaN, whereas the barrier layer **304** is or comprises AlGaIn. As such, in at least some embodiments, the channel layer **302** is or comprises a group III-V semiconductor (e.g., GaN or the like) and the barrier layer **304** is or comprises the group III-V semiconductor plus an additional element (e.g., aluminum or the like). Notwithstanding the specific semiconductor materials and/or elements enumerated above, other suitable semiconductor materials and/or elements are amenable for the channel layer **302** and the barrier layer **304**.

(69) A buffer layer **308** separates the first semiconductor substrate **102** from the support substrate **112**. In at least some embodiments in which the support substrate **112** is crystalline, the buffer layer **308** may serve as a seed for epitaxially growing the first semiconductor substrate **102** on the support substrate **112** and/or may buffer mismatches between lattice constants, coefficients of thermal expansion, and so on between the first semiconductor substrate **102** and the support substrate **112**. In some embodiments, the buffer layer **308** is a semiconductor layer. Further, in

some embodiments in which the channel layer **302** and the barrier layer **304** are respectively GaN and AlGaIn, the buffer layer **308** may be or comprise aluminum nitride, AlGaIn, GaN, some other suitable material, or any combination of the foregoing.

(70) The first active device **108** is a HEMT, but may be a MOSFET or some other suitable type of active device in alternative embodiments. The first active device **108** comprises a pair of source/drain electrodes **310** and a gate electrode **312** between the source/drain electrodes **310**. Further, the first active device **108** comprises a cap layer **314** separating the gate electrode **312** from the first semiconductor substrate **102**. Source/drain electrode(s) may refer to a source or a drain, individually or collectively dependent upon the context. The source/drain electrodes **310** and the gate electrode **312** are conductive and may, for example, be metal or the like. The cap layer **314** is a semiconductor material and is polarized to change conductivity of the two-dimensional carrier gas **306** at the gate electrode **312**. For example, the cap layer **314** may deplete the two-dimensional carrier gas **306** of mobile carriers at the gate electrode **312**. In some embodiments, the cap layer **314** is doped and/or is a group III-V semiconductor material, a group II-VI semiconductor material, or the like. For example, the cap layer **314** may be or comprise p-doped GaN or some other suitable semiconductor material.

(71) In some embodiments, the channel layer **302** is or comprises GaN, the barrier layer **304** is or comprises AlGaIn, the buffer layer **308** is or comprises GaN, the cap layer **314** is or comprises p-doped GaN, and the support substrate **112** is or comprises monocrystalline silicon. Further, in at least some of such embodiments, the first semiconductor substrate **102**, the support substrate **112**, and the buffer layer **308** define a GaN on silicon substrate.

(72) The second active devices **116** comprise a p-type MOSFET **116p** and an n-type MOSFET **116n** formed in part by the second semiconductor substrate **104**. In alternative embodiments, the second active devices **116** have some other suitable configuration or are some other suitable type of active device. The p-type MOSFET **116p** is at an n-type well **316** in the second semiconductor substrate **104**, and the n-type MOSFET **116n** is at a bulk of the second semiconductor substrate **104**. In alternative embodiments, the n-type well **316** is omitted, the p-type MOSFET **116p** is at the bulk of the second semiconductor substrate **104**, and the n-type MOSFET **116n** is at a p-type well in the second semiconductor substrate **104**.

(73) The second active devices **116** comprise individual body contact regions **318**, individual source/drain regions **320**, individual gate electrodes **322**, and individual gate dielectric layers **324**. Source/drain region(s) may refer to a source or a drain, individually or collectively dependent upon the context. The body contact regions **318** and the source/drain regions **320** correspond to doped regions of the second semiconductor substrate **104**. The gate electrodes **322** are sandwiched between corresponding source/drain regions **320** and are separated from the second semiconductor substrate **104** by the gate dielectric layers **324**.

(74) The passive devices **118** comprise a metal-insulator-metal (MIM) capacitor **118m**, an inductor **118i**, and a transformer **118t** in the second frontside interconnect structure **120**. In alternative embodiments, more or less passive devices and/or different types of passive devices than those illustrated may be in the second frontside interconnect structure **120**. The MIM capacitor **118m** comprises a first electrode **326**, a second electrode **328**, and an insulator layer **330** separating the first and second electrodes **326**, **328**. The inductor **118i** is spiral shaped but may have other suitable shapes. The transformer **118t** is schematically illustrated and may be formed by conductive features of the second frontside interconnect structure **120**.

(75) The first and second frontside interconnect structures **110**, **120** define conductive paths **332** electrically coupling the first and second active devices **108**, **116** and the passive devices **118** together to form a circuit. For example, a conductive path may electrically couple the MIM capacitor **118m** to the first active device **108**. As another example, another conductive path may electrically couple the first active device **108** to a source/drain region **320** of the n-type MOSFET **116n**. As another example, other conductive paths may electrically couple the first active device

108 to the inductor **118i** and the transformer **118t**.

(76) With reference to FIGS. **4A** and **4B**, circuit diagrams **400A**, **400B** respectively of some different embodiments of the 3D IC of FIG. **3** are provided.

(77) As illustrated by the circuit diagram **400A** of FIG. **4A**, the 3D IC is or comprises an LLC power converter. An input voltage V_{in} is input into the LLC power converter, and an output voltage V_{out} is output from the LLC power converter. The input voltage V_{in} may, for example, be about 40-140 volts or some other suitable value, and/or the output voltage V_{out} may, for example, be about 1-20 volts or some other suitable voltage. In some embodiments, the input voltage V_{in} is or is about 48 volts and the output voltage V_{out} is or is about 5 or 12 volts. In some embodiments, the input and output voltages V_{in} , V_{out} are directed current (DC).

(78) The LLC power converter comprises a plurality of active devices **402** and a plurality of passive devices **404**, which are interconnected by the first and second frontside interconnect structures **110**, **120** of FIG. **3**. The plurality of active devices **402** include HEMTs **402h**, and the plurality of passive devices **404** include capacitors **404c**, inductors **404i**, a transformer **404t**, and diodes **404d**. The first active device **108** of FIG. **3** and/or the second active devices **116** of FIG. **3** correspond to the active devices **402**. For example, the first active device **108** of FIG. **3** may correspond to one of the HEMTs **402h**. The passive devices **118** of FIG. **3** correspond to the passive devices **404**. For example, the MIM capacitor **118m** of FIG. **3** may correspond to one of the capacitors **404c**, the inductor **118i** of FIG. **3** may correspond to one of the inductors **404i**, and the transformer **118t** of FIG. **3** may correspond to the transformer **404t**.

(79) As noted above, in some embodiments, the first semiconductor substrate **102** of FIG. **3** has a larger bandgap than the second semiconductor substrate **104** of FIG. **3**. In at least some of such embodiments, active devices of the LLC power converter that benefit from the larger bandgap (e.g., the active devices **402**) are on and partially formed by the first semiconductor substrate **102**. Further, active devices that don't benefit or minimally benefit from the larger bandgap of the first semiconductor substrate **102** are on and partially formed by the second semiconductor substrate **104**. At least when the second semiconductor substrate **104** is or comprises monocrystalline silicon, this may reduce cost without compromising performance.

(80) As illustrated by the circuit diagram **400B** of FIG. **4B**, the 3D IC is or comprises a full-bridge power converter. An input voltage V_{in} is input into the full-bridge power converter, and an output voltage V_{out} is output from the full-bridge power converter. The input voltage V_{in} may, for example, be about 150-300 volts, about 300-650 volts, or some other suitable value, and/or the output voltage V_{out} may, for example, be about 40-140 volts or some other suitable voltage. In some embodiments, the input voltage V_{in} is or is about 208 volts and the output voltage V_{out} is or is about 48 volts. In some embodiments, the input voltage V_{in} is alternating current (AC), whereas the output voltage V_{out} is DC.

(81) The full-bridge power converter comprises a plurality of active devices **406** and a plurality of passive devices **408**, which are interconnected by the first and second frontside interconnect structures **110**, **120** of FIG. **3**. The plurality of active devices **406** include HEMTs **406h** and MOSFETs **406m**, and the plurality of passive devices **408** include capacitors **408c**, inductors **408i**, and a transformer **408t**. The first and second active devices **108**, **116** of FIG. **3** correspond to the active devices **406**. For example, the first active device **108** of FIG. **3** may correspond to one of the HEMTs **406h**, and the second active devices **116** of FIG. **3** may correspond to the MOSFETs **406m**. The passive devices **118** of FIG. **3** correspond to the passive devices **408**. For example, the MIM capacitor **118m** of FIG. **3** may correspond to one of the capacitors **408c**, the inductor **118i** of FIG. **3** may correspond to one of the inductors **408i**, and the transformer **118t** of FIG. **3** may correspond to the transformer **408t**.

(82) As noted above, in some embodiments, the first semiconductor substrate **102** of FIG. **3** has a larger bandgap than the second semiconductor substrate **104** of FIG. **3**. In at least some of such embodiments, active devices of the full-bridge power converter that benefit from the larger

bandgap (e.g., the HEMTs **406h**) are on and partially formed by the first semiconductor substrate **102**. Further, active devices that don't benefit or minimally benefit from the larger bandgap of the first semiconductor substrate **102** (e.g., the MOSFETs **406m**) are on and partially formed by the second semiconductor substrate **104**. At least when the second semiconductor substrate **104** is or comprises monocrystalline silicon, this may reduce cost without compromising performance.

(83) With reference to FIGS. 5A-5C, cross-sectional views **500A-500C** of some alternative embodiments of the 3D IC of FIG. 3 are provided.

(84) As illustrated by the cross-sectional view **500A** of FIG. 5A, the first and second IC chips **106**, **114** are bonded together backside to frontside as described with regard to FIG. 2A. As such, the first IC chip **106** further comprises a backside interconnect structure **202** and TSVs **204**, which contribute to the conductive paths **332**.

(85) As illustrated by the cross-sectional view **500B** of FIG. 5B, the first and second IC chips **106**, **114** are bonded together frontside to backside as described with regard to FIG. 2B. As such, the second IC chip **114** further comprises a backside interconnect structure **206** and TSVs **208**, which contribute to the conductive paths **332**.

(86) As illustrated by the cross-sectional view **500C** of FIG. 5C, the first and second IC chips **106**, **114** are bonded together backside to backside as described with regard to FIG. 2C. As such, the first IC chip **106** is as in FIG. 5A, and the second IC chip **114** is as in FIG. 5B, except that the conductive paths **332** are different at the backside interconnect structure **202** of the first IC chip **106** and the backside interconnect structure **206** of the second IC chip **114**.

(87) With reference to FIG. 6, a cross-sectional view **600** of some more detailed embodiments of the 3D IC of FIG. 3 is provided in which the first and second frontside interconnect structures **110**, **120** have additional detail. In particular, the first and second frontside interconnect structures **110**, **120** comprise a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in corresponding interconnect dielectric layers **608** to define conductive paths (e.g., the conductive paths **332** of FIG. 3).

(88) The pads **606** are grouped in a plurality of pad layers individual to the first and second frontside interconnect structures **110**, **120**, and the pad layers directly contact at the bond interface **122**. The vias **602** and the wires **604** are grouped in a plurality of via layers and a plurality of wire layers. Via layers and wire layers at the first frontside interconnect structure **110** are alternately stacked from the pad layer of the first frontside interconnect structure **110** to the first active device **108**. Similarly, via layers and wire layers at the second frontside interconnect structure **120** are alternately stacked from the pad layer of the second frontside interconnect structure **120** to the second active devices **116**. The vias **602**, the wires **604**, and the pads **606** are conductive and may, for example, be or comprise copper, aluminum, aluminum copper, the like, or any combination of the foregoing.

(89) With reference to FIGS. 7A-7C, cross-sectional views **700A-700C** of some alternative embodiments of the 3D IC of FIG. 6 are provided.

(90) As illustrated by the cross-sectional view **700A** of FIG. 7A, the first and second IC chips **106**, **114** are bonded together backside to frontside as described with regard to FIG. 2A and/or FIG. 5A. As such, the first IC chip **106** further comprises a backside interconnect structure **202** and TSVs **204**. Note that the TSVs **204** may be separated from the first semiconductor substrate **102** and the support substrate **112** by corresponding TSV dielectric layers (not shown) in some embodiments.

(91) As illustrated by the cross-sectional view **700B** of FIG. 7B, the first and second IC chips **106**, **114** are bonded together frontside to backside as described with regard to FIG. 2B and/or FIG. 5B. As such, the second IC chip **114** further comprises a backside interconnect structure **206** and TSVs **208**. Note that the TSVs **208** may be separated from the second semiconductor substrate **104** by corresponding TSV dielectric layers (not shown) in some embodiments.

(92) The backside interconnect structure **202** of FIG. 7A and the backside interconnect structure **206** of FIG. 7B are as of the first and second frontside interconnect structures **110**, **120** are

described, whereby the backside interconnect structures **202**, **206** comprise a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in a corresponding interconnect dielectric layer **608**. Further, note that the wires **604** of the backside interconnect structures **202**, **206** may also be known as RDLs or the like.

(93) As illustrated by the cross-sectional view **700C** of FIG. 7C, the first and second IC chips **106**, **114** are bonded together backside to backside as described with regard to FIG. 2C and/or FIG. 5C. As such, the first IC chip **106** is as in FIG. 7A, and the second IC chip **114** is as in FIG. 7B, except that the conductive paths are different at the backside interconnect structures **202**, **206** of the first and second IC chips **106**, **114**.

(94) With reference to FIG. 8, a cross-sectional view **800** of some alternative embodiments of the 3D IC of FIG. 1 is provided in which the 3D IC comprises additional IC chips. In particular, the 3D IC further comprises a third IC chip **802** and a fourth IC chip **804** stacked over the first and second IC chips **106**, **114**.

(95) The first and second IC chips **106**, **114** are as described with regard to FIG. 1, except that the second IC chip **114** further comprises the backside interconnect structure **206** and the TSV **208** described with regard to FIG. 2B. Further, the third and fourth IC chips **802**, **804** are respectively as the first and second IC chips **106**, **114** are described with regard to FIG. 1, except that the third IC chip **802** further comprises the backside interconnect structure **202** and the TSV **204** described with regard to FIG. 2A. Because the third and fourth IC chips **802**, **804** are as the first and second IC chips **106**, **114** are described with regard to FIG. 1, constituents of the third IC chip **802** use the same reference numbers as the first IC chip **106**, and constituents of the fourth IC chip **804** use the same reference numbers as the second IC chip **114**.

(96) The first and second IC chips **106**, **114** are bonded together frontside to frontside, the third and fourth IC chips **802**, **804** are bonded together frontside to frontside, and the second and third IC chips **114**, **802** are bonded together backside to backside. Further, the backside interconnect structures **202**, **206** and the TSVs **204**, **208** provide electrical coupling between the frontside interconnect structures **120**, **110** of the second and third IC chips **114**, **802**.

(97) In some embodiments, the 3D IC is or comprises a full-bridge converter and an LLC power converter. In at least some of such embodiments, the first and second IC chips **106**, **114** substantially or wholly define the full-bridge power converter, and the third and fourth IC chips **802**, **804** substantially or wholly define the LLC power converter electrically coupled in series with the full-bridge power converter. For example, an output of the full-bridge power converter is electrically coupled to an input of the LLC power converter. The full-bridge power converter may, for example, be as described with regard to FIGS. 3 and 4B, whereas the LLC power converter may, for example, be as described with regard to FIGS. 3 and 4A.

(98) As schematically illustrated, an input voltage V_{in} is provided to full-bridge power converter at the first IC chip **106**, and the full-bridge power converter reduces the input voltage to an intermediate voltage V_i less than the input voltage V_{in} at a bond interface between the second and third IC chips **114**, **802**. The LLC power converter then reduces the intermediate voltage V_i to an output voltage V_{out} less than the intermediate voltage V_i at the fourth IC chip **804**. The input voltage V_{in} may, for example, be about 150-300 volts, about 300-650 volts, or some other suitable value, the intermediate voltage V_i may, for example, be about 40-140 volts or some other suitable voltage, and/or the output voltage V_{out} may, for example, be about 1-20 volts or some other suitable voltage. In some embodiments, the input voltage V_{in} is or is about 208 volts, the intermediate voltage V_i is or is about 48 volts, and the output voltage V_{out} is or is about 5 or 12 volts. In some embodiments, the input voltage V_{in} is AC, whereas the intermediate voltage V_i and the output voltage V_{out} are DC.

(99) In some embodiments, the semiconductor substrates **102** of the first and third IC chips **106**, **802** have a wider bandgap than the semiconductor substrates **104** of the second and fourth IC chips **114**, **804**. For example, the semiconductor substrates **102** of the first and third IC chips **106**, **802**

may be or comprise GaN or the like, whereas the semiconductor substrates **104** of the second and fourth IC chips **114**, **804** may be or comprise monocrystalline silicon or the like. Further, in at least some of such embodiments, active devices that benefit from the wider bandgap are formed on the semiconductor substrates **102** of the first and third IC chips **106**, **802**, whereas active devices that don't benefit or minimally benefit from the wider bandgap are formed on the semiconductor substrates **104** of the second and fourth IC chips **114**, **804**. In embodiments in which the semiconductor substrates **104** of the second and fourth IC chips **114**, **804** are or comprise silicon, this may lead to reduced costs without compromising performance since silicon is generally cheaper to work with than other semiconductor materials.

(100) With reference to FIGS. **9A-9H**, cross-sectional views **900A-900H** of some alternative embodiments of the 3D IC of FIG. **8** are provided in which orientations of the first, second, third, and fourth IC chips **106**, **114**, **802**, **804** are varied.

(101) As illustrated by the cross-sectional view **900A** of FIG. **9A**, the fourth IC chip **804** is vertically flipped relative to FIG. **8**. As a result, the third and fourth IC chips **802**, **804** are bonded together frontside to backside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. **2B**.

(102) As illustrated by the cross-sectional view **900B** of FIG. **9B**, the third and fourth IC chips **802**, **804** are each vertically flipped relative to FIG. **8**. As a result, the third and fourth IC chips **802**, **804** are bonded together backside to backside, and the second and third IC chips **114**, **802** are bonded together backside to frontside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. **2B**.

(103) As illustrated by the cross-sectional view **900C** of FIG. **9C**, the second IC chip **114** is vertically flipped relative to FIG. **8**. As a result, the first and second IC chips **106**, **114** are bonded together frontside to backside. Further, the second and third IC chips **114**, **802** are bonded together frontside to backside.

(104) As illustrated by the cross-sectional view **900D** of FIG. **9D**, the second IC chip **114** and the fourth IC chip **804** are each vertically flipped relative to FIG. **8**. As a result, the first and second IC chips **106**, **114** are bonded together frontside to backside, the second and third IC chips **114**, **802** are bonded together frontside to backside, and the third and fourth IC chips **802**, **804** are bonded together frontside to backside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. **2B**.

(105) As illustrated by the cross-sectional view **900E** of FIG. **9E**, the second IC chip **114**, the third IC chip **802**, and the fourth IC chip **804** are each vertically flipped relative to FIG. **8**. As a result, the first and second IC chips **106**, **114** are bonded together frontside to backside, the second and third IC chips **114**, **802** are bonded together frontside to frontside, the second and third IC chips **114**, **802** are bonded together frontside to frontside, and the third and fourth IC chips **802**, **804** are bonded together backside to backside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. **2B**.

(106) As illustrated by the cross-sectional view **900F** of FIG. **9F**, the first IC chip **106** and the second IC chip **114** are each vertically flipped relative to FIG. **8**. As a result, the first and second IC chips **106**, **114** are bonded together backside to backside, and the second and third IC chips **114**, **802** are bonded together frontside to backside. Further, the first IC chip **106** further comprises a backside interconnect structure **202** and a TSV **204** as described with regard to FIG. **2A**.

(107) As illustrated by the cross-sectional view **900G** of FIG. **9G**, the first IC chip **106**, the second IC chip **114**, and the fourth IC chip **804** are each vertically flipped relative to FIG. **8**. As a result, the first and second IC chips **106**, **114** are bonded together backside to backside, the second and third IC chips **114**, **802** are bonded together frontside to backside, and the third and fourth IC chips **802**, **804** are bonded together frontside to backside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. **2B**, and the first IC chip **106** further comprises a backside interconnect structure **202** and a TSV

204 as described with regard to FIG. 2A.

(108) As illustrated by the cross-sectional view **900H** of FIG. 9H, the first IC chip **106**, the second IC chip **114**, the third IC chip **802**, and the fourth IC chip **804** are each vertically flipped relative to FIG. 8. As a result, the first and second IC chips **106**, **114** are bonded together backside to backside, the second and third IC chips **114**, **802** are bonded together frontside to frontside, and the third and fourth IC chips **802**, **804** are bonded together backside to backside. Further, the fourth IC chip **804** further comprises a backside interconnect structure **206** and a TSV **208** as described with regard to FIG. 2B, and the first IC chip **106** further comprises a backside interconnect structure **202** and a TSV **204** as described with regard to FIG. 2A.

(109) With reference to FIG. 10, a cross-sectional view **1000** of some embodiments of the 3D IC of FIG. 8 is provided in which the 3D IC has additional detail. The first IC chip **106** is as described with regard to FIG. 6, and the third IC chip **802** is as the first IC chip **106** is described with regard to FIG. 7A. The second IC chip **114** is as described with regard to FIG. 7B, and the fourth IC chip **804** is as the second IC chip **114** is described with regard to FIG. 6.

(110) As above, in some embodiments, the 3D IC is or comprises a full-bridge converter and an LLC power converter electrically coupled in series. The first and second IC chips **106**, **114** substantially or wholly define the full-bridge power converter, and the third and fourth IC chips **802**, **804** substantially or wholly define the LLC power converter electrically coupled in series with the full-bridge power converter. The full-bridge power converter may, for example, be as described with regard to FIGS. 3 and 4B, whereas the LLC power converter may, for example, be as described with regard to FIGS. 3 and 4A.

(111) With reference to FIG. 11, a cross-sectional view **1100** of some alternative embodiments of the 3D IC of FIG. 1 is provided in which the 3D IC is applied to RF. A plurality of first RF devices **1102** is on and partially formed by the first semiconductor substrate **102**, whereas a plurality of second RF devices **1104** is on the second semiconductor substrate **104**. Because the first RF devices **1102** are partially formed by the first semiconductor substrate **102**, the first RF devices **1102** may also be referred to as first RF semiconductor devices. In some embodiments, one, some, or all of the second RF devices **1104** is/are partially formed by the second semiconductor substrate **104**, whereby these one or more RF devices may also be referred to as second RF semiconductor device(s). In some embodiments, the first RF devices **1102** are active RF devices, whereas one, some, or all of the second RF devices **1104** is/are passive RF devices. In some embodiments, the first RF devices **1102** are semiconductor devices, and/or one, some, or all of the second RF devices **1104** is/are semiconductor devices.

(112) The first and second RF devices **1104** may, for example, be interconnected by the first and second frontside interconnect structures **110**, **120** to define a FEM, a transceiver, an MMIC, or some other suitable RF circuit. The first RF devices **1102** may, for example, include a low noise amplifier (LNA) **1102_l**, an RF switch **1102_s**, and a power amplifier (PA) **1102_p**. The second RF devices **1104** may, for example, include a plurality of filters **1104_f**, a resistor-inductor-capacitor (RLC) input matching network **1104_{ri}**, and an RLC output matching network **1104_{ro}**. Additional and/or alternative RF devices are, however, amenable.

(113) In some embodiments, the first semiconductor substrate **102** has a larger bandgap than the second semiconductor substrate **104**. For example, the first semiconductor substrate **102** may be or comprise GaN or the like, whereas the second semiconductor substrate **104** may be or comprise monocrystalline silicon or the like. The larger bandgap leads to smaller RC parasitic elements, which allows active RF devices on and partially formed by the first semiconductor substrate **102** to operate at high frequencies. Therefore, to the extent that the first semiconductor substrate **102** has the larger bandgap, active RF devices that benefit from the larger bandgap (e.g., the first RF devices **1102**) may be formed on and partially formed by the first semiconductor substrate **102**. On the other hand, RF devices that don't benefit or minimally benefit from the larger bandgap of the first semiconductor substrate **102** (e.g., the second RF devices **1104**) may be formed on the second

semiconductor substrate **104**. This may reduce costs with little to no performance tradeoff because forming RF devices on non-silicon substrates tends to be more costly than forming RF devices on silicon substrates.

(114) With reference to FIG. **12**, a circuit diagram **1200** of some embodiments of the 3D IC of FIG. **11** is provided in which the 3D IC comprises a plurality of receive-transmit (Rx/Tx) chain pairs **1202**. The Rx/Tx chain pairs **1202** are configured to couple to individual antennas **1204**, which are external to the 3D IC. For clarity, bounds of the 3D IC are schematically represented by a box **1206** separating the Rx/Tx chain pairs **1202** from the antennas **1204**.

(115) Each of the Rx/Tx chain pairs **1202** comprises a receive chain **1208**, a transmit chain **1210**, and a pair of RF switches **1102s**. Further, each of the Rx/Tx chain pairs **1202** is configured to operate in a transmit mode and a receive mode. For each of the Rx/Tx chain pairs **1202**, the receive chain **1208** of that Rx/Tx chain pair and the transmit chain **1210** of that Rx/Tx chain pair are electrically coupled between the RF switches **1102s** of that Rx/Tx chain pair. In the receive mode of that Rx/Tx chain pair, the RF switches **1102s** of that Rx/Tx chain pair electrically couple the receive chain **1208** of that Rx/Tx chain pair to input/output ports of that Rx/Tx chain pair. In the transmit mode of that Rx/Tx chain pair, the RF switches **1102s** of that Rx/Tx chain pair electrically couple the transmit chain **1210** of that Rx/Tx chain pair to the input/output ports of that Rx/Tx chain pair. The individual antenna **1204** of that Rx/Tx chain pair is electrically coupled to one of the input/output ports of that Rx/Tx chain pair, and an RF combiner/splitter circuit **1212** shared by the Rx/Tx chain pairs **1202** is electrically coupled to another one of the input/output ports of that Rx/Tx chain pair.

(116) The receive and transmit chains **1208**, **1210** of the Rx/Tx chain pairs **1202** comprise corresponding filters **1104f**, corresponding RLC input matching network **1104ri**, corresponding RLC output matching network **1104ro**, and corresponding envelope trackers **1102et**. Further, the receive chains **1208** comprise corresponding LNAs **1102i**, whereas the transmit chains **1210** comprise corresponding PAs **1102p**. The envelope trackers **1102et** are included amongst the first RF devices **1102** of FIG. **11** and hence are on and partially formed by the first semiconductor substrate **102** of FIG. **11**. The envelope trackers **1102et** comprise corresponding variable amplifiers **1214** and corresponding variable phase shifters **1216**.

(117) The RF combiner/splitter circuit **1212** comprises a plurality of RF combiners/splitters **1104c**. The RF combiners/splitters **1104c** are configured to split a transmit signal to be transmit with the Rx/Tx chain pairs **1202**, and are further configured to combine signals received with the Rx/Tx chain pairs **1202** into a single receive signal. The RF combiners/splitters **1104c** are included amongst the second RF devices **1104** of FIG. **11** and hence are on and partially formed by the second semiconductor substrate **104** of FIG. **11**. In alternative embodiments, of RF combiners/splitters **1104c** have some other suitable configuration. Further, in alternative embodiments, the RF combiner/splitter circuit **1212** additionally or alternatively comprises RF dividers, RF transmission lines, the like, or any combination of the foregoing.

(118) With reference to FIGS. **13A** and **13B**, schematic views **1300A**, **1300B** of some embodiments respectively of the first and second IC chips **106**, **114** of the 3D IC of FIGS. **11** and **12** are provided in which devices of the 3D IC are split amongst the first and second IC chips **106**, **114**. For example, the first RF devices **1102** are at the first IC chip **106** as illustrated by FIG. **13A**, whereas the second RF devices **1104** are at the second IC chip **114** as illustrated by FIG. **13B**. Note that electrical coupling between the first and second RF devices **1102**, **1104** is not shown in FIGS. **13A** and **13B**, but is performed by the first and second frontside interconnect structures **110**, **120** illustrated in FIG. **11**.

(119) With reference to FIG. **14**, a schematic view **1400** of some embodiments of the 3D IC of FIGS. **13A** and **13B** is provided in which the second IC chip **114** is overlaid on the first IC chip **106** to schematically represent stacking of the first and second IC chips **106**, **114** in the 3D IC. Note that bounds of the RLC input matching networks **1104ri** have a greater line weight compared to the

RLC output matching networks **1104ri** to schematically distinguish the RLC input matching networks **1104ri** from the RLC output matching networks **1104ro**.

(120) With reference to FIG. 15, a cross-sectional view **1500** of some embodiments of the 3D IC of FIG. 11 is provided in which constituents of the 3D IC have additional detail. The first semiconductor substrate **102** overlies the support substrate **112** and is or comprises a heterojunction structure. Further, the heterojunction structure comprises a channel layer **302** and a barrier layer **304** as described with regard to FIGS. 3 and 6. The channel layer **302** and the barrier layer **304** are semiconductor layers having unequal bandgaps and are or comprise group III-V semiconductor materials, group II-VI semiconductor materials, or the like. The channel layer **302** underlies and directly contacts the barrier layer **304** at a heterojunction. Further, the channel layer **302** accommodates a two-dimensional carrier gas **306**.

(121) A buffer layer **308** separates the first semiconductor substrate **102** and/or the heterojunction from the support substrate **112**. In at least some embodiments in which the support substrate **112** is crystalline, the buffer layer **308** may serve as a seed for epitaxially growing the first semiconductor substrate **102** on the support substrate **112** and/or may buffer mismatches between lattice constants, coefficients of thermal expansion, and so on between the first semiconductor substrate **102** and the support substrate **112**.

(122) The first RF devices **1102** are or comprise HEMTs as described with regard to FIGS. 3 and 6. However, in alternative embodiments, one, some, or all of the first RF devices **1102** may be MOSFET(s) and/or some other suitable type(s) of active RF device. The first RF devices **1102** comprise individual pairs of source/drain electrodes **310**, individual gate electrodes **312** between corresponding source/drain electrodes **310**, and individual cap layers **314** separating corresponding gate electrode **312** from the first semiconductor substrate **102**.

(123) The first and second frontside interconnect structures **110**, **120** comprise a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in corresponding interconnect dielectric layers **608** as described with regard to FIG. 6. Such stacking defines conductive paths electrically coupling the first and second RF devices **1102**, **1104** together to form a circuit. The circuit may, for example, correspond to a FEM, a transceiver, a MMIC, or the like and/or may, for example, correspond to the circuit at FIG. 12.

(124) With reference to FIGS. 16A-16C, cross-sectional views **1600A-1600C** of some alternative embodiments of the 3D IC of FIG. 15 are provided in which the first and second IC chips **106**, **114** of the 3D IC have different orientations.

(125) As illustrated by the cross-sectional view **1600A** of FIG. 16A, the first IC chip **106** is vertically flipped, such that the first and second IC chips **106**, **114** are bonded together backside to frontside at the bond interface **122**. As a result, the first IC chip **106** further comprises a backside interconnect structure **202** and TSVs **204**. Note that the TSVs **204** may be separated from the first semiconductor substrate **102** and the support substrate **112** by corresponding TSV dielectric layers (not shown) in some embodiments.

(126) The backside interconnect structure **202** overlies the first semiconductor substrate **102** on the backside **102bs** of the first semiconductor substrate **102**, and the TSVs **204** extend through the first semiconductor substrate **102** from the backside interconnect structure **202** to the first frontside interconnect structure **110** to provide electrical coupling therebetween. The backside interconnect structure **202** is as the first and second frontside interconnect structures **110**, **120** are described, whereby the backside interconnect structure **202** comprises a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in a corresponding interconnect dielectric layer **608** to define conductive paths.

(127) As illustrated by the cross-sectional view **1600B** of FIG. 16B, the second IC chip **114** is vertically flipped, such that the first and second IC chips **106**, **114** are bonded together frontside to backside at the bond interface **122**. As a result, the second IC chip **114** further comprises a backside interconnect structure **206** and TSVs **208**. Note that the TSVs **208** may be separated from the

second semiconductor substrate **104** by corresponding TSV dielectric layers (not shown) in some embodiments.

(128) The backside interconnect structure **206** underlies the second semiconductor substrate **104** on the backside **104bs** of the second semiconductor substrate **104**, and the TSVs **208** extend through the second semiconductor substrate **104** from the backside interconnect structure **206** to the second frontside interconnect structure **120** to provide electrical coupling therebetween. The backside interconnect structure **206** is as the first and second frontside interconnect structures **110**, **120** are described, whereby the backside interconnect structure **206** comprise a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in a corresponding interconnect dielectric layer **608** to define conductive paths.

(129) As illustrated by the cross-sectional view **1600C** of FIG. **16C**, the first and second IC chips **106**, **114** are each vertically flipped, such that the first and second IC chips **106**, **114** are bonded together backside to backside at the bond interface **122**. The first IC chip **106** is as in FIG. **16A**, whereas the second IC chip **114** is as in FIG. **16B**.

(130) With reference to FIG. **17**, a cross-sectional view **1700** of some alternative embodiments of the 3D IC of FIG. **11** is provided in which the 3D IC further comprises an antenna **1204**. The antenna **1204** is included amongst the second RF devices **1104** and is therefore on the second semiconductor substrate **104** at the second IC chip **114**.

(131) With reference to FIG. **18**, a perspective view **1800** of some embodiments of the antenna **1204** of FIG. **17** is provided. The antenna **1204** comprises a conductive ground plate **1802** and a conductive patch **1804** overlying the conductive ground plate **1802**. Further, the antenna **1204** comprises a dielectric layer **1806** separating the conductive ground plate **1802** from the conductive patch **1804**.

(132) With reference to FIG. **19**, a circuit diagram **1900** of some embodiments of the 3D IC of FIG. **17** is provided. The circuit diagram **1900** is as the circuit diagram **1200** of FIG. **12** is described, except that the antennas **1204** are included in the 3D IC. For clarity, bounds of the 3D IC are schematically represented by the box **1206**. The antennas **1204** may, for example, each be as illustrated and described with regard to FIG. **18**.

(133) With reference to FIG. **20**, a cross-sectional view **2000** of some embodiments of the 3D IC of FIG. **17** is provided in which constituents of the 3D IC have additional detail. In particular, the 3D IC is as illustrated and described with regard to FIG. **15**, except that the 3D IC further comprises the antenna **1204** on the second semiconductor substrate **104**. In alternative embodiments, the first and second IC chips **106**, **114** may be bonded together backside to frontside, frontside to backside, and backside to backside respectively as in FIGS. **16A-16C**. Put another way, the antenna **1204** may be on the second semiconductor substrate **104** in alternative embodiments of the 3D ICs of FIGS. **16A-16C**.

(134) With reference to FIG. **21**, a cross-sectional view **2100** of some alternative embodiments of the 3D IC of FIG. **11** is provided in which the 3D IC further comprises an antenna **1204**, a mixer **2102**, a local oscillator **2104**, and an RLC matching network **1104r**. Note that the RLC matching network **1104r** may correspond to the RLC input matching network **1104ri** of FIG. **11** or the RLC output matching network **1104ro** of FIG. **11**. The antenna **1204**, the mixer **2102**, and the local oscillator **2104** are included amongst the second RF devices **1104** and are therefore on the second semiconductor substrate **104** at the second IC chip **114**. In alternative embodiments, the mixer **2102** and/or the local oscillator **2104** is/are included amongst the first RF devices **1102** and is/are therefore on the first semiconductor substrate **102** at the first IC chip **106**. The first and second RF devices **1102**, **1104** may, for example, be interconnected by the first and second frontside interconnect structures **110**, **120** to define a FEM, a transceiver, an MMIC, or some other suitable RF circuit.

(135) With reference to FIG. **22**, a circuit diagram **2200** of some embodiments of the 3D IC of FIG. **21** is provided in which the 3D IC comprises a receive chain **1208**, a transmit chain **1210**, an RF

switch **1102s**, an antenna **1204**, and a plurality of local oscillators **2104**. The RF switch **1102s** is included amongst the first RF devices **1102** of FIG. **21** and hence is on and partially formed by the first semiconductor substrate **102** of FIG. **21**. The antenna **1204** and the local oscillators **2104** are included amongst the second RF devices **1104** of FIG. **21** and hence are on and partially formed by the second semiconductor substrate **104** of FIG. **21**. In alternative embodiments, the antenna **1204** is external to the 3D IC. Further, in alternative embodiments, the local oscillators **2104** are included amongst the first RF devices **1102** of FIG. **21** and hence are on and partially formed by the first semiconductor substrate **102** of FIG. **21**.

(136) The receive and transmit chains **1208**, **1210** are configured to electrically couple to a baseband processing circuit **2202**, which is external to the 3D IC. For clarity, bounds of the 3D IC are schematically represented by a box **2204** separating the Rx/Tx chain pairs **1202** from the baseband processing circuit **2202**. The baseband processing circuit **2202** may, for example, be configured for demodulation, analog-to-digital conversion, digital signal processing, baseband processing, digital-to-analog conversion, modulation, and so on. Additionally, the receive and transmit chains **1208**, **1210** are electrically coupled to the RF switch **1102s**, which is configured to selectively electrically couple the receive and transmit chains **1208**, **1210** to the antenna **1204**. In a transmit mode, the RF switch **1102s** is configured to electrically couple the transmit chain **1210** to the antenna **1204**. In a receive mode, the RF switch **1102s** is configured to electrically couple the receive chain **1208** to the antenna.

(137) The receive and transmit chains **1208**, **1210** comprise corresponding filters **1104f**, corresponding RLC input matching network **1104ri**, and corresponding RLC output matching network **1104ro**. Further, the receive chain **1208** comprises a LNA **11021** and a mixer **2102**, whereas the transmit chain **1210** comprises a PA **1102p** and an up-converter **1104u**. The LNA **11021** and the PA **1102p** are included amongst the first RF devices **1102** of FIG. **21** and hence are on and partially formed by the first semiconductor substrate **102** of FIG. **21**. The RLC input and output matching networks **1104ri**, **1104ro** correspond to the RLC matching network of FIG. **21**. The RLC input matching networks **1104ri**, the RLC output matching networks **1104ro**, the filters **1104f**, the mixer **2102**, and the up-converter **1104u** are included amongst the second RF devices **1104** of FIG. **21** and hence are on and partially formed by the second semiconductor substrate **104** of FIG. **21**. Further, the mixer **2102** and the up-converter **1104u** correspond to the local oscillators **2104** with a one-to-one correspondence or some other suitable correspondence.

(138) With reference to FIG. **23**, a cross-sectional view **2300** of some embodiments of the 3D IC of FIG. **21** is provided in which constituents of the 3D IC have additional detail. In particular, the 3D IC is as illustrated and described with regard to FIG. **15**, except that the 3D IC further comprises the antenna **1204**, the mixer **2102**, and the local oscillator **2104**. In alternative embodiments, the first and second IC chips **106**, **114** may be bonded together backside to frontside, frontside to backside, and backside to backside respectively as in FIGS. **16A-16C**.

(139) With reference to FIGS. **24-26**, a series of cross-sectional views **2400-2600** of some embodiments of a method for forming a 3D IC comprising semiconductor substrates with different bandgaps is provided. As seen hereafter, the method may, for example, be employed to form the 3D IC of FIG. **6** or some other suitable 3D IC.

(140) As illustrated by the cross-sectional view **2400** of FIG. **24**, a first IC chip **106** is formed. More particularly, a first semiconductor substrate **102** is formed overlying a support substrate **112**, such that the support substrate **112** is on a backside **102bs** of the first semiconductor substrate. Further, a first active device **108** and a first frontside interconnect structure **110** are formed overlying the first semiconductor substrate **102** on a frontside **102fs** of the first semiconductor substrate, opposite the backside **102bs**.

(141) The first semiconductor substrate **102** is or comprises a heterojunction structure. Further, the heterojunction structure comprises a channel layer **302** and a barrier layer **304** as described with regard to FIGS. **3** and **6**. The channel layer **302** and the barrier layer **304** are semiconductor layers

having unequal bandgaps and are or comprise group III-V semiconductor materials, group II-VI semiconductor materials, or the like. The channel layer **302** underlies and directly contacts the barrier layer **304** at a heterojunction. Further, the channel layer **302** accommodates a two-dimensional carrier gas **306**.

(142) A buffer layer **308** separates the first semiconductor substrate **102** and/or the heterojunction from the support substrate **112**. In at least some embodiments in which the support substrate **112** is crystalline, the buffer layer **308** may serve as a seed for epitaxially growing the first semiconductor substrate **102** on the support substrate **112** and/or may buffer mismatches between lattice constants, coefficients of thermal expansion, and so on between the first semiconductor substrate **102** and the support substrate **112**.

(143) In some embodiments, the support substrate **112** is or comprises monocrystalline silicon, silicon carbide, sapphire, or some other suitable semiconductor material. In some embodiments, the first semiconductor substrate **102** and the support substrate **112** form a composite substrate. To the extent that the first semiconductor substrate **102** is or comprises GaN and the support substrate is or comprises monocrystalline silicon, silicon carbide, or sapphire, the composite substrate may be or comprise a GaN on silicon substrate, a GaN on silicon carbide substrate, or a GaN on sapphire substrate.

(144) The first active device **108** is between the first semiconductor substrate **102** and the first frontside interconnect structure **110** and is partially formed by the first semiconductor substrate **102**. Further, the first active device **108** is or comprises a HEMT as described with regard to FIGS. **3** and **6**. In alternative embodiments, the first active device **108** may be some other suitable type of active device. The first active devices **108** comprise a pair of source/drain electrode **310**, a gate electrode **312** between the source/drain electrodes **310**, and a cap layer **314** separating the gate electrode **312** from the first semiconductor substrate **102**.

(145) The first frontside interconnect structures **110** comprises a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in an interconnect dielectric layer **608** as described with regard to FIG. **6**. Such stacking defines conductive paths extending from the first active device **108** to facilitate formation of a circuit.

(146) As illustrated by a cross-sectional view **2500** of FIG. **25**, a second IC chip **114** is formed. More particularly, a plurality of second active device **116**, a plurality of passive devices **118**, and a second frontside interconnect structure **120** are formed on a frontside **104fs** of a second semiconductor substrate **104** which is opposite a backside **104bs** of the second semiconductor substrate **104**.

(147) The second active devices **116** are between the second semiconductor substrate **104** and the second frontside interconnect structure **120** and are partially formed by the second semiconductor substrate **104**. Further, the second active devices **116** comprises a p-type MOSFET **116p** and an n-type MOSFET **116n**. In alternative embodiments, the second active devices **116** have some other suitable configuration or are some other suitable type of active device. The p-type MOSFET **116p** is at an n-type well **316** in the second semiconductor substrate **104**, and the n-type MOSFET **116n** is at a bulk of the second semiconductor substrate **104**. In alternative embodiments, the n-type well **316** is omitted, the p-type MOSFET **116p** is at the bulk of the second semiconductor substrate **104**, and the n-type MOSFET **116n** is at a p-type well in the second semiconductor substrate **104**. The second active devices **116** comprise individual body contact regions **318**, individual source/drain regions **320**, individual gate electrodes **322**, and individual gate dielectric layers **324**.

(148) The passive devices **118** are in the second frontside interconnect structure **120**. In alternative embodiments, one, some, or all of the passive devices **118** is/are in the first frontside interconnect structure **110** of FIG. **24**. Further, the passive devices **118** comprise a metal-insulator-metal (MIM) capacitor **118m**, an inductor **118i**, and a transformer **118t**. In alternative embodiments, more or less passive devices and/or different types of passive devices than those illustrated may be in the second frontside interconnect structure **120**.

(149) The second semiconductor substrate **104** has a different bandgap than the first semiconductor substrate **102**. For example, the first semiconductor substrate **102** may have a larger or wider bandgap than the second semiconductor substrate **104** or vice versa. In some embodiments in which the first semiconductor substrate **102** has the larger bandgap, the first semiconductor substrate **102** may be or comprise GaN or the like, whereas the second semiconductor substrate **104** may be or comprise monocrystalline silicon or the like.

(150) The second frontside interconnect structures **120** comprises a plurality of vias **602**, a plurality of wires **604**, and a plurality of pads **606** stacked in an interconnect dielectric layer **608** as described with regard to FIG. **6**. Such stacking defines conductive paths extending from the second active devices **116** and the passive devices **118** to facilitate formation of a circuit.

(151) As illustrated by a cross-sectional view **2600** of FIG. **26**, the second IC chip **114** is vertically flipped and is bonded to the first IC chip **106** frontside to frontside at a bond interface **122**. The bonding is performed frontside to frontside in that the frontside **102fs** of the first semiconductor substrate **102** and the frontside **104fs** of the second semiconductor substrate **104** face each other. The bonding comprises both: 1) bonding (e.g., direct bonding, fusion bonding, etc.) between the interconnect dielectric layers **608** of the first and second frontside interconnect structures **110**, **120**; and 2) bonding (e.g., direct bonding, fusion bonding, etc.) between the pads **606** of the first and second frontside interconnect structures **110**, **120**. The first and second semiconductor substrates **102**, **104** may, for example, correspond to portions of semiconductor wafers before singulation, whereby the bonding may, for example, be regarded as wafer-to-wafer bonding or the like.

(152) By bonding the first and second IC chips **106**, **114** together, the first and second IC chips **106**, **114** are physical secured to each other and are electrically coupled to each other. Such electrical coupling forms a circuit. The circuit may, for example, be a full-bridge power converter, an LLC power converter, or the like. An example of the LLC power converter is at FIG. **4A**, whereas an example of the full-bridge power converter is at FIG. **4B**.

(153) In at least some embodiments in which the circuit is the LLC power converter of FIG. **4A**, the HEMTs **402h** of FIG. **4A** are formed on and partially formed by the first semiconductor substrate **102** and the first active device **108** corresponds to one of these HEMTs **402h**. Further, the passive devices **404** of FIG. **4A** are formed at the second IC chip **114** and correspond to the passive devices **118**. For example, the MIM capacitor **118m** may correspond to one of the capacitors **404c** of FIG. **4A**, the transformer **118t** may correspond to the transformer **404t** of FIG. **4A**, and the inductor **118i** may correspond to one of the inductors **404i** of FIG. **4A**.

(154) In at least some embodiments in which the circuit is the full-bridge power converter of FIG. **4B**, the HEMTs **406h** of FIG. **4B** are formed on and partially formed by the first semiconductor substrate **102** and the first active device **108** corresponds to one of these HEMTs **406h**. Further, the MOSFETs **406m** of FIG. **4B** are formed on and partially formed by the second semiconductor substrate **104** and the second active devices **108** correspond to these MOSFETs **406m**. Further yet, the passive devices **408** of FIG. **4B** are formed at the second IC chip **114** and correspond to the passive device **118**. For example, the MIM capacitor **118m** may correspond to one of the capacitors **408c** of FIG. **4B**, the transformer **118t** may correspond to the transformer **408t** of FIG. **4B**, and the inductor **118i** may correspond to one of the inductors **408i** of FIG. **4B**.

(155) As noted above, the first semiconductor substrate **102** may have a larger or wider bandgap than the second semiconductor substrate **104**. To the extent that the first semiconductor substrate **102** has the larger bandgap, active devices that benefit from the larger bandgap (e.g., the first active device **108**) are on and partially formed by the first semiconductor substrate **102**. Active devices used for power supplies, power conversion, and so on tend to benefit from the larger bandgap because the larger bandgap enables operation at higher frequencies, higher voltages, and higher temperatures. Further, active devices that don't benefit or minimally benefit from the larger bandgap (e.g., the second active devices **116**) may be formed on the second semiconductor substrate **104**. At least when the second semiconductor substrate **104** is or comprises

monocrystalline silicon, this may reduce cost because forming active devices using non-silicon substrates tends to be more costly than using silicon substrates.

(156) Additionally, because the first and second IC chips **106**, **114** are vertically stacked, wire length between the first and second IC chips **106**, **114** is small and area consumed by the 3D IC is small. The small wire lengths may lead to reduced parasitic inductance and capacitance and may hence enhance performance. The small area may allow enhanced functional density on a PCB or other substrate to which the 3D IC is mounted and may hence reduce costs.

(157) While the first and second IC chips **106**, **114** are illustrated as being bonded together frontside to frontside, the first and second IC chips **106**, **114** may alternatively be bonded together backside to frontside, frontside to backside, or backside to backside respectively as illustrated at FIGS. 7A-7C. In such alternative embodiments, the first IC chip **106** is further formed at FIG. 24 with a backside interconnect structure **202** and TSVs **204** and/or the second IC chip **114** is further formed at FIG. 25 with a backside interconnect structure **206** and TSVs **208**.

(158) In some embodiments, the first and second semiconductor substrates **102**, **104** correspond to portions of semiconductor wafers. In at least some of such embodiments, the method may proceed from the acts of FIG. 26 to singulation of the semiconductor wafers, thereby separating the first and second IC chips **106**, **114** from replicas of the first and second IC chips **106**, **114** on the semiconductor wafers. Additionally, in at least some embodiments, the method may proceed from the acts of FIG. 26 to packaging of the 3D IC formed by the first and second IC chips **106**, **114**.

(159) While FIGS. 24-26 are described with reference to a method, it will be appreciated that the structures shown in FIGS. 24-26 are not limited to the method but rather may stand alone separate of the method. While FIGS. 24-26 are described as a series of acts, it will be appreciated that the order of the acts may be altered in other embodiments. While FIGS. 24-26 illustrate and describe as a specific set of acts, some acts that are illustrated and/or described may be omitted in other embodiments. Further, acts that are not illustrated and/or described may be included in other embodiments. For example, while FIGS. 24-26 focus on formation of the 3D IC using chip-to-chip or wafer-to-wafer bonding, the 3D IC may be alternatively formed by transferring the second semiconductor substrate **104** to the first IC chip **106** or by depositing the second semiconductor substrate **104** on the first IC chip **106**. In both cases, the second active devices **116**, the passive devices **118**, and the second frontside interconnect structure **120** are formed on the second semiconductor substrate **104** after the transfer or the deposition. FIGS. 2G and 2H provide non-limiting examples of such 3D ICs.

(160) With reference to FIG. 27, a block diagram **2700** of some embodiments of the method of FIGS. 24-26 is provided.

(161) At **2702**, a first IC chip is formed. The first IC chip comprises a first semiconductor substrate and a first semiconductor device on and partially formed by the first semiconductor substrate. See, for example, FIG. 24.

(162) At **2704**, a second IC chip is formed. The second IC chip comprises a second semiconductor substrate and a second semiconductor device on and partially formed by the second semiconductor substrate. Further, the second semiconductor substrate has a different bandgap than the first semiconductor substrate. For example, the first semiconductor substrate may be or comprise GaN, whereas the second semiconductor substrate may be or comprise silicon. Other suitable materials are, however, amenable. See, for example, FIG. 25.

(163) At **2706**, the first and second IC chips are bonded and electrically coupled together while the second IC chip overlies the first IC chip. Such bonding may, for example, be performed frontside to frontside, backside to frontside, frontside to backside, or backside to backside. Further, the bonding forms a circuit spread across the first and second IC chips. The circuit may, for example, be or comprise a full-bridge power converter, an LLC power converter, or some other suitable circuit. See, for example, FIG. 26.

(164) While the block diagram **2700** of FIG. 27 is illustrated and described herein as a series of acts

or events, it will be appreciated that the illustrated ordering of such acts or events is not to be interpreted in a limiting sense. For example, some acts may occur in different orders and/or concurrently with other acts or events apart from those illustrated and/or described herein. Further, not all illustrated acts may be required to implement one or more aspects or embodiments of the description herein, and one or more of the acts depicted herein may be carried out in one or more separate acts and/or phases.

(165) As illustrated above, the method of FIGS. **24-26** may complete with the support substrate **112** on the backside **102bs** of the first semiconductor substrate **102** and the 3D IC may then proceed to packaging with the support substrate **112** in place. However, in alternative embodiments of the method of FIGS. **24-26**, the method may further include removing the support substrate **112** as illustrated by a cross-sectional view **2800** of FIG. **28**. The removal may, for example, occur after the bonding at FIG. **26** and may, for example, be performed by etching, chemical mechanical planarization (CMP), some other suitable removal process(es), or any combination of the foregoing. Removing the support substrate **112** may, for example, reduce RF substrate loss and/or enhance thermal dissipation.

(166) With reference to FIGS. **29-31**, a series of cross-sectional views **2900-3100** of some alternative embodiments of the method of FIGS. **24-26** is provided in which semiconductor devices of the 3D IC correspond to RF. As seen hereafter, the method may, for example, be employed to form the 3D IC of FIG. **15** or some other suitable 3D IC.

(167) As illustrated by a cross-sectional view **2900** of FIG. **29**, the first IC chip **106** is formed as described with regard to FIG. **24**. However, in contrast with FIG. **24** in which a first active device **108** is formed on the first semiconductor substrate **102**, a plurality of first RF devices **1102** is formed on the first semiconductor substrate **102**. The first RF devices **1102** may, for example, include a LNA **1102l**, an RF switch **1102s**, and a PA **1102p**. Additional and/or alternative RF devices are, however, amenable.

(168) The first RF devices **1102** are between the first semiconductor substrate **102** and the first frontside interconnect structure **110** and are partially formed by the first semiconductor substrate **102**. Further, the first RF devices **1102** are or comprise HEMTs as described with regard to FIGS. **3** and **6**. In alternative embodiments, one, some, or all of the first RF devices **1102** may be MOSFET(s) and/or some other suitable type(s) of active RF device. The first RF devices **1102** comprise individual pairs of source/drain electrodes **310**, individual gate electrodes **312** between corresponding source/drain electrodes **310**, and individual cap layers **314** separating corresponding gate electrode **312** from the first semiconductor substrate **102**.

(169) As illustrated by a cross-sectional view **3000** of FIG. **30**, a second IC chip **114** is formed as described with regard to FIG. **25**. However, in contrast with FIG. **25** in which second active devices **116** and passive devices **118** are formed on the second semiconductor substrate **104**, a plurality of second RF devices **1104** is formed on the second semiconductor substrate **104**.

(170) The second RF devices **1104** are between the second semiconductor substrate **104** and the second frontside interconnect structure **120**. In some embodiments, one, some, or all of the second RF devices **1104** is/are partially formed by the second semiconductor substrate **104**. Further, in alternative embodiments, one, some, or all of the second RF devices **1104** is/are in the second frontside interconnect structure **120**. The second RF devices **1104** may, for example, include a plurality of filters **1104f**, a resistor-inductor-capacitor (RLC) input matching network **1104ri**, an RLC output matching network **1104ro**. Additional and/or alternative RF devices are, however, amenable. For example, the second RF devices **1104** may further include an antenna, a mixer, a local oscillator, and so on as described illustrated at FIGS. **20** and **23**.

(171) As illustrated by a cross-sectional view **3100** of FIG. **31**, the second IC chip **114** is vertically flipped and is bonded to the first IC chip **106** frontside to frontside at a bond interface **122** as described with regard to FIG. **26**. By bonding the first and second IC chips **106**, **114** together, the first and second IC chips **106**, **114** form a circuit. The circuit may, for example, be a FEM, a

transceiver, a MMIC, or the like. Examples of the circuit are at FIGS. **12**, **19**, and **22**.

(172) As noted above, the first semiconductor substrate **102** may have a larger or wider bandgap than the second semiconductor substrate **104**. To the extent that the first semiconductor substrate **102** has the larger bandgap, RF devices that benefit from the larger bandgap (e.g., the first RF devices **1102**) are on and partially formed by the first semiconductor substrate **102**. Active devices used for RF tend to benefit from the larger bandgap because the larger bandgap enables operation at higher frequencies, higher voltages, and higher temperatures. Further, RF devices that don't benefit or minimally benefit from the larger bandgap (e.g., the first RF devices **1104**) may be formed on the second semiconductor substrate **104**. At least when the second semiconductor substrate **104** is or comprises monocrystalline silicon, this may reduce cost because forming RF devices using non-silicon substrates tends to be more costly.

(173) While the first and second IC chips **106**, **114** are illustrated as being bonded together frontside to frontside, the first and second IC chips **106**, **114** may alternatively be bonded together backside to frontside, frontside to backside, or backside to backside respectively as illustrated at FIGS. **16A-16C**. In such alternative embodiments, the first IC chip **106** is further formed at FIG. **29** with a backside interconnect structure **202** and TSVs **204** and/or the second IC chip **114** is further formed at FIG. **30** with a backside interconnect structure **206** and TSVs **208**.

(174) While FIGS. **29-31** are described with reference to a method, it will be appreciated that the structures shown in FIGS. **29-31** are not limited to the method but rather may stand alone separate of the method. While FIGS. **29-31** are described as a series of acts, it will be appreciated that the order of the acts may be altered in other embodiments. While FIGS. **29-31** illustrate and describe as a specific set of acts, some acts that are illustrated and/or described may be omitted in other embodiments. Further, acts that are not illustrated and/or described may be included in other embodiments. For example, while FIGS. **29-31** focus on formation of the 3D IC using chip-to-chip or wafer-to-wafer bonding, the 3D IC may be alternatively formed by transferring the second semiconductor substrate **104** to the first IC chip **106** or by depositing the second semiconductor substrate **104** on the first IC chip **106**. In both cases, the second RF devices **1104** and the second frontside interconnect structure **120** are formed on the second semiconductor substrate **104** after the transfer or the deposition.

(175) In some embodiments, the present disclosure provides a 3D IC, including: a first IC chip including a first semiconductor substrate and a first semiconductor device on and partially formed by the first semiconductor substrate; and a second IC chip including a second semiconductor substrate and a second semiconductor device on and partially formed by the second semiconductor substrate; wherein the first and second IC chips are vertically stacked and are bonded together, and wherein the first semiconductor substrate has a larger band gap than the second semiconductor substrate. In some embodiments, the first semiconductor substrate includes gallium nitride, and the second semiconductor substrate includes silicon. In some embodiments, the 3D IC further includes a power converter formed in part by the first semiconductor device and formed in part by the second semiconductor device. In some embodiments, the first and second semiconductor devices are active semiconductor devices. In some embodiments, the 3D IC further includes: a third IC chip including a third semiconductor substrate and a third semiconductor device on and partially formed by the third semiconductor substrate; and a fourth IC chip including a fourth semiconductor substrate and a fourth semiconductor device on and partially formed by the fourth semiconductor substrate; wherein the first, second, third, and fourth IC chips are vertically stacked and are bonded together, and wherein the first and third semiconductor substrates share a first common bandgap, which is larger than a second bandgap shared by the second and fourth semiconductor substrates. In some embodiments, the 3D IC further includes: a first power converter circuit formed by the first and second IC chips; and a second power converter circuit formed by the third and fourth IC chips; wherein the first and second power converter circuits are electrically coupled together in series to convert a first voltage at the first IC chip to a second voltage at the fourth IC chip, and wherein the

second voltage is less than the first voltage.

(176) In some embodiments, the present disclosure provides another 3D IC, including: a first semiconductor substrate; a first device and a first interconnect structure on the first semiconductor substrate, wherein the first device is on and partially formed by the first semiconductor substrate, and is between the first semiconductor substrate and the first interconnect structure; a second semiconductor substrate overlying the first semiconductor substrate and the first interconnect structure; and a second device and a second interconnect structure on the second semiconductor substrate, wherein the second device is between the second semiconductor substrate and the second interconnect structure; wherein the first and second semiconductor substrates respectively include different semiconductor types. In some embodiments, the first and second devices are transistors formed in part by the different semiconductor types, respectively. In some embodiments, the first semiconductor substrate includes a group III-V heterojunction structure. In some embodiments, the 3D IC further includes a RF circuit formed in part by the first and second devices and including a transceiver and/or a FEM. In some embodiments, the first device is an active device, and the second device is a passive device. In some embodiments, the second device is a RF antenna. In some embodiments, the first and second devices and the first and second interconnect structures are between the first and second semiconductor substrates. In some embodiments, the first semiconductor substrate is between the first and second interconnect structures. In some embodiments, the second semiconductor substrate is between the first and second interconnect structures.

(177) In some embodiments, the present disclosure provides a method for forming a 3D IC, the method including: forming a first IC chip including a first semiconductor substrate and a first device on and partially formed by the first semiconductor substrate; forming a second IC chip including a second semiconductor substrate and a second device on the second semiconductor substrate; and bonding and electrically coupling the first and second IC chips together while the second IC chip overlies the first IC chip; wherein the first semiconductor substrate has a different band gap than the second semiconductor substrate. In some embodiments, the bonding including: bonding individual dielectric layers of the first and second IC chips together at a bond interface; and bonding individual metal pads of the first and second IC chips together at the bond interface. In some embodiments, the second device is partially formed by the second semiconductor substrate, which has a lesser bandgap than the first semiconductor substrate. In some embodiments, the first device is a HEMT, and the second device is a local oscillator or a mixer. In some embodiments, the first IC chip includes a support substrate on which the first semiconductor substrate is arranged, and the method further includes removing the support substrate after the bonding.

(178) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A three-dimensional (3D) integrated circuit (IC), comprising: a first IC chip comprising a first semiconductor substrate and a first semiconductor device on and partially formed by the first semiconductor substrate; a second IC chip comprising a second semiconductor substrate and a second semiconductor device on and partially formed by the second semiconductor substrate; a third IC chip and a fourth IC chip; a first power converter circuit formed by the first and second IC

chips; and a second power converter circuit formed by the third and fourth IC chips; wherein the first, second, third, and fourth IC chips are vertically stacked and are bonded together, wherein the first semiconductor substrate has a larger band gap than the second semiconductor substrate, and wherein the first and second power converter circuits are electrically coupled together in series to convert a first voltage at the first IC chip to a second voltage less than the first voltage at the fourth IC chip.

2. The 3D IC according to claim 1, wherein the first semiconductor substrate comprises gallium nitride, and wherein the second semiconductor substrate comprises silicon.

3. The 3D IC according to claim 1, wherein the first power converter circuit is formed in part by the first semiconductor device and is formed in part by the second semiconductor device.

4. The 3D IC according to claim 1, wherein the first and second semiconductor devices are active semiconductor devices.

5. The 3D IC according to claim 1, wherein the third IC chip comprises a third semiconductor substrate and a third semiconductor device on and partially formed by the third semiconductor substrate, wherein the fourth IC chip comprises a fourth semiconductor substrate and a fourth semiconductor device on and partially formed by the fourth semiconductor substrate, and wherein the first and third semiconductor substrates share a first common bandgap, which is larger than a second bandgap shared by the second and fourth semiconductor substrates.

6. A three-dimensional (3D) integrated circuit (IC), comprising: a first semiconductor substrate; a first device and a first interconnect structure on the first semiconductor substrate, wherein the first device is on and partially formed by the first semiconductor substrate, and is between the first semiconductor substrate and the first interconnect structure; a second semiconductor substrate overlying the first semiconductor substrate and the first interconnect structure; a second device and a second interconnect structure on the second semiconductor substrate, wherein the second device is between the second semiconductor substrate and the second interconnect structure; and a third semiconductor device in the first or second interconnect structure, spaced from the first and second semiconductor substrates, wherein the first and second semiconductor substrates respectively comprise different semiconductor types.

7. The 3D IC according to claim 6, wherein the first and second devices are transistors formed in part by the different semiconductor types, respectively.

8. The 3D IC according to claim 6, wherein the first semiconductor substrate comprises a group III-V heterojunction structure.

9. The 3D IC according to claim 6, further comprising: a radio frequency (RF) circuit formed in part by the first and second devices and comprising a transceiver and/or a front-end module (FEM).

10. The 3D IC according to claim 6, wherein the first device is an active device, and wherein the second device is a passive device.

11. The 3D IC according to claim 6, wherein the second device is a radio frequency (RF) antenna.

12. The 3D IC according to claim 6, wherein the first and second devices and the first and second interconnect structures are between the first and second semiconductor substrates.

13. The 3D IC according to claim 6, wherein the first semiconductor substrate has a wider bandgap than the second semiconductor substrate and is between the first and second interconnect structures, and wherein the 3D IC further comprises: a through substrate via extending through the first semiconductor substrate to electrically couple the first and second interconnect structures together.

14. A method for forming a three-dimensional (3D) integrated circuit (IC), the method comprising: forming a first IC chip comprising a first semiconductor substrate, a first device on and partially formed by the first semiconductor substrate, and a first interconnect structure; forming a second IC chip comprising a second semiconductor substrate, and a second device on the second semiconductor substrate, and a second interconnect structure; and bonding and electrically coupling the first and second IC chips together while the second IC chip overlies the first IC chip and while

the first and second interconnect structures are between the first and second semiconductor substrates; wherein the first semiconductor substrate has a different band gap than the second semiconductor substrate, and wherein the first and second interconnect structures each comprise multiple levels of wires and multiple levels of vias that are alternatingly and vertically stacked away from corresponding semiconductor substrates.

15. The method according to claim 14, wherein the bonding comprising: bonding individual dielectric layers of the first and second IC chips together at a bond interface; and bonding individual metal pads of the first and second IC chips together at the bond interface.

16. The method according to claim 14, wherein the first device is a high-electron-mobility transistor (HEMT), and wherein the second device is a local oscillator or a mixer.

17. The method according to claim 14, wherein the first IC chip comprises a support substrate on which the first semiconductor substrate is arranged, and wherein the method further comprises: removing the support substrate after the bonding.

18. The 3D IC according to claim 6, further comprising: a third semiconductor substrate and a fourth semiconductor substrate that are stacked with the first and second semiconductor substrates; a first power converter on the first and second semiconductor substrates; and a second power converter on the third and fourth semiconductor substrate, wherein the first and second power converters are electrically coupled together in series to convert a first voltage at the first semiconductor substrate to a second voltage less than the first voltage at the fourth semiconductor substrate.

19. The 3D IC according to claim 18, wherein the first and third semiconductor substrates share a first common bandgap, which is larger than a second bandgap shared by the second and fourth semiconductor substrates.

20. The method according to claim 14, further comprising: forming a third IC chip and a fourth IC chip; and bonding the third and fourth IC chips to the second IC chip with the third IC chip being between the second and fourth IC chips, wherein the first and second IC chips are formed with a first power converter circuit, wherein the third and fourth IC chips are formed with a second power converter circuit, and wherein the first and second power converter circuits are electrically coupled together in series to convert a first voltage at the first IC chip to a second voltage less than the first voltage at the fourth IC chip.
