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### Silicon optical phase shifter with a series of P—N junctions

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#### Abstract

An apparatus includes a silicon (Si) optical phase shifter. In an embodiment, the optical phase shifter comprises a planar optical waveguide having a silicon optical core, and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core. The segment of the silicon optical core comprises a series of p-n junctions. The series extends in a direction transverse to an optical propagation direction in a segment of the planar optical waveguide including the segment of the silicon optical core. At least two of the p-n junctions are configured to be reverse biased by applying a voltage across the biasing electrodes.

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## Background/Summary

### TECHNICAL FIELD

(1) Various example embodiments relate to the field of optical communications.

### BACKGROUND

(2) In silicon (Si) photonics, a Si optical phase shifter is widely used in different kinds of optical devices, such as a Si optical modulator. Unfortunately, some Si optical phase shifters suffer from capacitance issues, especially at higher frequencies.

### SUMMARY

(3) Various embodiments provide a Si optical phase shifter with a plurality of lateral p-n junctions. In general, when a p-n junction is biased at a reverse voltage, the p-n junction operates in carrier depletion mode where carriers drift out of and into a Si optical waveguide. The plasma/carrier dispersion effect (e.g., carrier depletion) generates an optical phase shift in light traveling along the Si optical waveguide. A Si optical phase shifter having multiple lateral p-n junctions in series reduces the overall capacitance of the Si optical waveguide. One technical benefit is a Si optical phase shifter as described herein may be used in higher frequency applications for high-speed or super high-speed operation, while maintaining similar modulation efficiency and/or optical loss as prior Si optical phase shifters.

(4) In an embodiment, an apparatus includes an optical phase shifter comprising a planar optical waveguide having a silicon optical core, and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core. The segment of the silicon optical core comprises a series of p-n junctions that extends in a direction transverse to an optical propagation direction in a segment of the planar optical waveguide including the segment of the silicon optical core. At least two of the p-n junctions are configured to be reverse biased by applying a voltage across the biasing electrodes.

(5) In an embodiment, at least another of the p-n junctions is located between the two of the p-n junctions and is configured to be forward biased by applying the voltage across the biasing electrodes.

(6) In an embodiment, the apparatus further comprises at least one radio-frequency traveling-wave electrode to operate the optical phase shifter.

(7) In an embodiment, the apparatus further comprises a Mach-Zehnder optical modulator having a parallel pair of optical waveguide arms, and the optical phase shifter is along one of the optical waveguide arms.

(8) In an embodiment, the apparatus further comprises at least one radio-frequency traveling-wave electrode configured to operate the optical phase shifter of the Mach-Zehnder optical modulator.

(9) In an embodiment, the apparatus further comprises an optical modulator comprising an optical ring resonator, and the optical phase shifter is along an optical waveguide segment of the optical ring resonator.

(10) In an embodiment, at least two of the p-n junctions are located on opposite sides of a lateral center of the silicon optical core in the segment thereof.

(11) In an embodiment, the planar optical waveguide has a geometry of a rib waveguide.

(12) In an embodiment, the planar optical waveguide includes a rib, with the rib being on a surface of the silicon optical core and being oriented along the optical propagation direction.

(13) In an embodiment, the rib comprises silicon nitride.

- (14) In an embodiment, a segment of the rib faces the segment of the silicon optical core comprising the series of p-n junctions.
- (15) In an embodiment, an apparatus includes a Mach-Zehnder optical modulator having a parallel pair of optical waveguide arms, where an optical phase shifter is along one of the optical waveguide arms. The optical phase shifter comprises a planar optical waveguide having a silicon optical core, and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core. The segment of the silicon optical core comprises a series of p-n junctions that extend in a direction transverse to an optical propagation direction in a segment of the planar optical waveguide including the segment of the silicon optical core. At least two of the p-n junctions are configured to be reverse biased by applying a voltage across the biasing electrodes.
- (16) In an embodiment, a method of fabricating a planar optical waveguide is disclosed. The method comprises acquiring a silicon substrate comprising a crystalline silicon layer formed on a lower optical cladding layer, etching the crystalline silicon layer to form a silicon optical core of the planar optical waveguide, and doping the silicon optical core to form a series of p-n junctions that extends in a direction transverse to an optical propagation direction in a segment of the planar optical waveguide. The method further comprises forming an upper optical cladding of the planar optical waveguide on the silicon optical core, and forming a pair of biasing electrodes along opposite sides of a segment of the silicon optical core.
- (17) One or more of the above embodiments may be combined as desired.
- (18) The above summary provides a basic understanding of some aspects of the specification. This summary is not an extensive overview of the specification. It is intended to neither identify key or critical elements of the specification nor delineate any scope of the particular embodiments of the specification, or any scope of the claims. Its sole purpose is to present some concepts of the specification in a simplified form as a prelude to the more detailed description that is presented later.
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## Description

### DESCRIPTION OF THE DRAWINGS

- (1) Some embodiments are now described, by way of example only, and with reference to the accompanying drawings. The same reference number represents the same element or the same type of element on all drawings.
- (2) FIG. 1 is a perspective view of a silicon (Si) optical phase shifter in an illustrative embodiment.
- (3) FIGS. 2-4 are cross-sectional views of a Si optical phase shifter in an illustrative embodiment.
- (4) FIGS. 5-7 are cross-sectional views of a Si optical phase shifter in an illustrative embodiment.
- (5) FIGS. 8-9 are schematic diagrams of a Si optical waveguide in an illustrative embodiment.
- (6) FIG. 10 is a flow chart illustrating a method of fabricating a Si optical phase shifter in an illustrative embodiment.
- (7) FIGS. 11-14 illustrate results of fabrication steps of the method in FIG. 10 in illustrative embodiments.
- (8) FIGS. 15-17 are cross-sectional views of a Si optical phase shifter in an illustrative embodiment.
- (9) FIGS. 18-20 are cross-sectional views of a Si optical phase shifter in an illustrative embodiment.
- (10) FIG. 21 is a flow chart illustrating a method of fabricating a Si optical phase shifter in an illustrative embodiment.
- (11) FIGS. 22-25 illustrate results of fabrication steps of the method in FIG. 21 in illustrative embodiments.
- (12) FIG. 26 illustrates optical devices that implement one or more Si optical phase shifters in an

illustrative embodiment.

(13) FIG. 27 illustrates an optical device that implements one or more Si Mach-Zehnder Modulators (MZM) in an illustrative embodiment.

(14) FIG. 28 illustrates an optical device that implements one or more optical ring resonators in an illustrative embodiment.

## DESCRIPTION OF EMBODIMENTS

(15) The figures and the following description illustrate specific exemplary embodiments. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the embodiments and are included within the scope of the claims. The inventive concepts are not limited to the specific embodiments or examples described below, but are defined by the claims and their equivalents.

(16) Herein, a silicon optical waveguide is a planar optical waveguide having a silicon optical core. Part(s) of the silicon optical core may be impurity doped, e.g., to form p-n and/or p-i-n junction(s) therein.

(17) FIG. 1 is a perspective view of a silicon (Si) optical phase shifter **100** in an illustrative embodiment. A Si optical phase shifter **100** is an optical device configured to control the phase of light by a change in effective refractive index (n). Si optical phase shifter **100** includes a Si optical waveguide **102** formed on a Si substrate **104**. For example, Si optical phase shifter **100** may be formed on a Silicon-On-Insulator (SOI) wafer having an insulating layer, such as silicon oxide, between a crystalline Si layer and the Si substrate **104**. Various layers of Si optical waveguide **102**, e.g., the silicon optical core, may be formed from the Si layers of the SOI wafer, and/or silicon subsequently deposited or formed. As will be described in more detail below, Si optical phase shifter **100** includes a plurality of lateral p-n junctions embedded in a segment **130** of Si optical waveguide **102**. Si optical phase shifter **100** employs carrier depletion as a mechanism to electrically modulate free carrier densities of the lateral p-n junctions in Si optical waveguide **102**. Carrier density variations are responsible for refractive index variations in Si optical waveguide **102**, and the phase of an optical signal propagating through Si optical waveguide **102** (i.e., along a light or optical propagation direction **132**) is modulated based on carrier density variations. For example, an optical signal **122** launched into Si optical waveguide **102** is phase modulated to produce a phase-modulated output signal **124**.

(18) FIGS. 2-4 are cross-sectional views of Si optical phase shifter **100** in an illustrative embodiment. The views in FIGS. 2-4 are across a transverse cut plane A-A (e.g., along the x-axis) as shown in FIG. 1, which is generally perpendicular to the light propagation direction **132** through Si optical waveguide **102** (e.g., along the y-axis). The Si optical waveguide **102** of Si optical phase shifter **100** includes a lower optical cladding layer **206**, a Si optical core **208**, and an upper optical cladding **210** in the vertical direction along the z-axis. The lower optical cladding layer **206** may comprise a layer of silicon dioxide (e.g., SiO<sub>2</sub>), such as a silicon buried oxide (BOX), or another type of dielectric that acts as a lower optical cladding for Si optical core **208**. Si optical core **208** may be a polycrystalline or amorphous Si overlayer in contact with the lower optical cladding layer **206**, and has a higher refractive index than the lower optical cladding layer **206**. Upper optical cladding **210** may comprise a layer of silicon dioxide or another optical cladding in contact with Si optical core **208** that has a lower refractive index than Si optical core **208**. Additional elements of Si optical phase shifter **100** may be incorporated as desired. Also, FIGS. 2-4 are not drawn to scale.

(19) In FIG. 2, Si optical phase shifter **100** includes a series **216** of lateral p-n junctions **212** in Si optical core **208**, where the series **216** extends perpendicular to the light propagation direction **132** in Si optical waveguide **102**, e.g., the p-n junctions **212** may approximately form a stack perpendicular to the light propagation direction **132**. A p-n junction **212** is an interface between a p-type silicon material and an n-type silicon material.

(20) In an embodiment, three p-n junctions **212** (i.e., first, second, and third lateral p-n junctions

**212-1, 212-2, and 212-3**) are located in a series **216** across a width of Si optical core **208**.

Electrically, the p-n junctions **212-1, 212-2, and 212-3** are series-connected across a direct voltage bias network. The lateral p-n junctions **212** are created by doping the crystalline Si material of the Si optical core **208**. The doping creates a first p-type region **220** and a first n-type region **222**, and creates a second p-type region **224** and a second n-type region **226**. The doping creates two lateral p-n junctions **212-1** and **212-3** of the same orientation, and another p-n junction **212-2** oppositely oriented. Lateral p-n junctions **212-1** and **212-3** are reverse-biased during operation, and p-n junction **212-2** is forward-biased during operation, when the entire series **216** is connected across a suitable DC biasing voltage source. Thus, p-n junctions **212-1** and **212-3** contribute to modulation when reverse-biased, while p-n junction **212-2** does not contribute to modulation. Although the series **216** of lateral p-n junctions includes two lateral p-n junctions **212** of the same p-n orientation as shown in FIG. 2, the series **216** may have more lateral p-n junction of the same p-n orientation in other embodiments.

(21) In an embodiment, a geometry of Si optical waveguide **102** comprises a rib optical waveguide **230**. The dimensions of Si optical core **208** as a rib optical waveguide **230** include a rib width **232**, a total optical core thickness **234**, and a rib height **236**. For example, the rib width **232** may be equal to or less than about 500 nanometers (nm), the total optical core thickness **234** may be equal to or less than about 220 nm, and rib height **236** may be in the range of about 80-120 nm, although other dimensions are considered herein. The lateral p-n junctions **212** are disposed or arranged in series across the rib width **232** in the Si optical core **208**.

(22) For a lateral p-n junction **212**, a p-type region contains an excess of holes, while an n-type region contains an excess of electrons. At or near a lateral p-n junction **212**, electrons may diffuse across to combine with holes creating a substantial “depletion region” in response to reverse-biasing. FIG. 3 schematically illustrates electrical operation of Si optical phase shifter **100** in FIG. 2, where a first depletion region **310** is formed at lateral p-n junction **212-1**, and a second depletion region **311** is formed at lateral p-n junction **212-3**. The first depletion region **310** and the second depletion region **311** are offset from the lateral center **318** (i.e., along the x-axis) of Si optical core **208**. Carrier density variations are responsible for refractive index variations in Si optical waveguide **102**. Thus, the phase of an optical signal propagating through Si optical waveguide **102** may be modulated by changing the carrier densities at the reversed-biased lateral p-n junctions **212**.

(23) In FIG. 4, carrier densities are represented by the width **440** of the depletion regions **310-311** at the lateral p-n junctions **212**. During operation, the width **440** may be adjusted by applying a varying reverse-biasing voltage from a voltage source **450** across the series **216** of lateral p-n junctions **212**. As is clear from FIG. 4, such biasing also causes the second p-n junction **212-2** to be forward-biased. Si optical phase shifter **100** further includes biasing electrodes **416-417** configured to electrically couple static (DC) voltage source **450** across the entire series **216** of p-n junctions **212** in Si optical core **208**. Electrodes **416-417** are located along opposite sides of a segment **430** of Si optical core **208**. Electrode **416** is electrically coupled via a heavily p-type doped (p++) portion of a Si slab **420** to the first p-type region **220**. Electrode **417** is electrically coupled via a heavily n-type doped (n++) portion of a Si slab **421** to the second n-type region **226**.

(24) FIGS. 5-7 are cross-sectional views of Si optical phase shifter **100** in an illustrative embodiment. The views in FIGS. 5-7 are across a transverse cut plane A-A (e.g., along the x-axis) as shown in FIG. 1. As above, Si optical waveguide **102** of Si optical phase shifter **100** includes lower optical cladding layer **206**, Si optical core **208**, and upper optical cladding **210** in the vertical direction along the z-axis. Additional elements of Si optical phase shifter **100** may be incorporated as desired. Also, FIGS. 5-7 are not drawn to scale.

(25) In FIG. 5, Si optical phase shifter **100** includes a plurality of lateral p-n junctions **212** embedded in Si optical waveguide **102**. In an embodiment, five lateral p-n junctions **212** (i.e., first, second, third, fourth, and fifth lateral p-n junctions **212-1, 212-2, 212-3, 212-4, and 212-5**) are located in a series **216** across a width of Si optical core **208**. The lateral p-n junctions **212** are

created by doping the crystalline Si material of the Si optical core **208**. The doping creates a first p-type region **520** and a first n-type region **522**, creates a second p-type region **524** and a second n-type region **526**, and creates a third p-type region **528** and a third n-type region **530**. The doping creates three lateral p-n junctions **212-1**, **212-3**, and **212-5** of the same orientation, and two other p-n junctions **212-2** and **212-4** oppositely oriented. Lateral p-n junctions **212-1**, **212-3**, and **212-5** are reverse-biased during operation, and p-n junctions **212-2** and **212-4** are forward-biased during operation, when the entire series **216** is connected across a suitable DC biasing voltage source. Thus, p-n junctions **212-1**, **212-3**, and **212-5** contribute to modulation when reverse-biased, while p-n junctions **212-2** and **212-4** do not contribute to modulation. Although the series **216** of lateral p-n junctions **212** includes three lateral p-n junctions **212** of the same p-n orientation in Si optical core **208** as shown in FIG. 5, the series **216** may have more lateral p-n junctions **212** of the same p-n orientation in other embodiments.

(26) FIG. 6 schematically illustrates electrical operation of Si optical phase shifter **100** in FIG. 5, where a first depletion region **610** is formed at lateral p-n junction **212-1**, a second depletion region **611** is formed at lateral p-n junction **212-3**, and a third depletion region **612** is formed at lateral p-n junction **212-5**. The first depletion region **610** and the third depletion region **612** are offset from the lateral center **318** (i.e., along the x-axis) of Si optical core **208**, while the second depletion region **611** is generally aligned with the lateral center **318**.

(27) In FIG. 7, carrier densities are represented by the width **440** of the depletion regions **610-612** at the lateral p-n junctions **212**. During operation, the width **440** may be adjusted by applying a varying reverse-biasing voltage from a voltage source **450** across the series **216** of lateral p-n junctions **212**. As is clear from FIG. 7, such biasing also causes the p-n junctions **212-2** and **212-4** to be forward-biased. Si optical phase shifter **100** further includes biasing electrodes **416-417** configured to electrically couple with voltage source **450** across the entire series **216** of p-n junctions **212** in Si optical core **208**. Electrodes **416-417** are located along opposite sides of a segment **430** of Si optical core **208**. Electrode **416** is electrically coupled via a heavily p-type doped (p++) portion of a Si slab **720** to the first p-type region **520**. Electrode **417** is electrically coupled via a heavily n-type doped (n++) portion of a Si slab **721** to the third n-type region **530**.

(28) One technical benefit of the configurations of a Si optical phase shifter **100** as discussed above is a lower capacitance is realized in the Si optical waveguide **102** while maintaining optical phase modulation efficiency. FIGS. 8-9 are schematic diagrams of Si optical waveguide **102** in an illustrative embodiment. FIG. 8 is a schematic diagram functionally illustrating electrical properties of the Si optical waveguide **102** shown in FIG. 4. During operation, resistor **802** represents the resistance across the Si optical core **208**. There is a capacitance between p-type and n-type regions of each reverse-biased p-n junction **212**. Thus, capacitor **804** represents the capacitance of reverse-biased p-n junction **212-1**, and capacitor **805** represents the capacitance of reverse-biased p-n junction **212-3** (see also, FIG. 4). The total capacitance of N capacitors in series is the inverse of the sum of the inverse of the individual capacitances. If, for example, two equal-valued capacitors are in series, the total capacitance is half of their value. Thus, when the capacitances of reverse-biased p-n junction **212-1** and p-n junction **212-3** are about equal, the total capacitance of the Si optical waveguide **102** is about half the capacitance of a single one of the reverse-biased p-n junctions **212**. As shown in FIG. 4, the two lateral p-n junctions **212**, which are reverse-biased in operation, are offset from the lateral center **318** of Si optical core **208** where optical intensity may typically be maximum, and the modulation efficiency may be somewhat lower than a design with a single p-n junction aligned with the lateral center **318**. However, the smaller capacitance across the Si optical core **208** can provide an advantage over a design with a single p-n junction, especially at higher frequencies.

(29) FIG. 9 is a schematic diagram functionally illustrating electrical properties of the Si optical waveguide **102** shown in FIG. 7. Again, during operation, resistor **902** represents the resistance across the Si optical core **208**. Capacitor **904** represents the capacitance of reverse-biased p-n

junction **212-1**, capacitor **905** represents the capacitance of reverse-biased p-n junction **212-3**, and capacitor **906** represents the capacitance of reverse-biased p-n junction **212-5** (see also, FIG. 7). As shown in FIG. 7, reverse-biased p-n junction **212-3** is approximately aligned with the lateral center **318** of Si optical core **208** where optical intensity may typically be maximum, and reverse-biased p-n junctions **212-1** and **212-5** are offset from the lateral center **318**. The modulation efficiency may therefore be similar to a design with a single p-n junction aligned with the lateral center **318**, but the smaller capacitance provides an advantage over a design with a single p-n junction, especially at higher frequencies.

(30) FIG. **10** is a flow chart illustrating a method **1000** of fabricating a Si optical phase shifter in an illustrative embodiment. The steps of the flow charts described herein are not all inclusive and may include other steps not shown, and the steps may be performed in an alternative order. FIGS. **11-14** illustrate results of the fabrication steps in illustrative embodiments.

(31) Method **1000** includes the step of acquiring or obtaining a Si substrate **104** (step **1002**). In FIG. **11**, the Si substrate **104** includes a crystalline Si layer **1108** formed on a lower optical cladding layer **206**. For example, an SOI wafer **1140** may be acquired having a crystalline Si layer (or device layer) of about 220 nm. In FIG. **10**, method **1000** further includes etching the crystalline Si layer **1108** to form a Si optical core **208** of a Si optical waveguide **102** (step **1004**). In FIG. **12**, for example, a resist **1212** may be patterned on the top surface **1118** of the crystalline Si layer **1108** (see FIG. **11**), and an etching process is performed (e.g., reactive ion etching process) to remove material from the crystalline Si layer **1108** down to an etching depth **1236**. The etching process forms the Si optical core **208** of the Si optical waveguide **102**. In this embodiment, the Si optical waveguide **102** has a geometry of a rib waveguide with a slab **1222** and a rib **1224**.

(32) In FIG. **10**, method **1000** further includes doping the Si optical core **208** to form a plurality of lateral p-n junctions **212** in the Si optical waveguide **102** (step **1006**). In FIG. **13**, with the resist **1212** removed, an ion implantation process **1306** or similar process may be performed to create p-type regions and n-type regions in the Si optical core **208** that form a series of lateral p-n junctions **212**. Although three lateral p-n junctions **212** are illustrated in FIG. **13**, more than three lateral p-n junctions **212** may be formed (see FIG. **5**). In FIG. **10**, method **1000** further includes forming an upper optical cladding **210** of the Si optical waveguide **102** on the Si optical core **208** (step **1008**). In FIG. **14**, the upper optical cladding **210** may be formed by depositing a Si material having a lower refractive index than the Si optical core **208**, such as silicon dioxide. In FIG. **10**, method **1000** further includes forming a pair of biasing electrodes **416-417** along opposite sides of a segment **430** of Si optical core **208** (step **1010**), as shown in FIG. **4**.

(33) Method **1000** may be performed in multiple areas of a Si substrate **104** to fabricate multiple Si optical phase shifters.

(34) FIGS. **15-17** are cross-sectional views of Si optical phase shifter **100** in an illustrative embodiment. The views in FIGS. **15-17** are across a transverse cut plane A-A (e.g., along the x-axis) as shown in FIG. **1**. The Si optical waveguide **102** of Si optical phase shifter **100** includes a lower optical cladding layer **1506**, a Si or hybrid-material optical core **1514** formed by Si layer **1508** and a light-guiding rib **1509**, and an upper optical cladding **1510** in the vertical direction along the z-axis. Lower optical cladding layer **1506** may comprise a layer of silicon dioxide (e.g., SiO<sub>2</sub>), such as a silicon buried oxide (BOX), or another type of dielectric that acts as a lower optical cladding for optical core **1514**. The Si or hybrid optical core **1514** has a Si overlayer **1508** in contact with the lower optical cladding layer **1506** that has a higher refractive index. The light-guiding rib **1509** may be a Si layer, to produce a Si optical core **1514**, or may be, e.g., a silicon nitride layer (SiN), that has a lower refractive index than silicon to produce a hybrid optical core **1514**. In the hybrid case, the light-guiding rib **1509** has a lower refractive index than Si layer **1508** and a higher refractive index than upper optical cladding **1510**. The upper optical cladding **1510** may comprise a layer of silicon dioxide or another dielectric in contact with the Si layer **1508** that has a lower refractive index. Additional elements of Si optical phase shifter **100** may be



incorporated as desired. Also, FIGS. 15-17 are not drawn to scale.

(35) In FIG. 15, Si optical phase shifter **100** includes a series **1516** of lateral p-n junctions **212** in optical core **1514**, where the series **1516** extends perpendicular to the light propagation direction **132** in Si optical waveguide **102**, e.g., the p-n junctions **212** may approximately form a stack perpendicular to the light propagation direction **132**. In an embodiment, three lateral p-n junctions **212** (i.e., first, second, and third lateral p-n junctions **212-1**, **212-2**, and **212-3**) are located in a series **1516** across a width of Si layer **1508**. The lateral p-n junctions **212** are created by doping the crystalline Si material of the Si layer **1508**. The doping creates a first p-type region **220** and a first n-type region **222**, and creates a second p-type region **224** and a second n-type region **226**. The doping creates two lateral p-n junctions **212-1** and **212-3** of the same orientation, and another p-n junction **212-2** oppositely oriented. Lateral p-n junctions **212-1** and **212-3** are reverse-biased during operation, and p-n junction **212-2** is forward-biased during operation, when the entire series **1516** is connected across a suitable DC biasing voltage source. Thus, p-n junctions **212-1** and **212-3** contribute to modulation when reverse-biased, while p-n junction **212-2** does not contribute to modulation. Although the series **1516** of lateral p-n junctions includes two lateral p-n junctions **212** of the same p-n orientation in Si layer **1508** as shown in FIG. 15, the series **1516** may have more lateral p-n junctions of the same p-n orientation in other embodiments.

(36) In an embodiment, a geometry of Si optical waveguide **102** comprises a strip-loaded waveguide **1530**. The dimensions of Si optical waveguide **102** as a strip-loaded waveguide **1530** include a width **1532** of the light-guiding rib **1509**, and a height **1534** of the Si layer **1508**. For example, the width **1532** may be equal to or less than about 500 nm, and the height **1534** may be equal to or less than about 110 nm, although other dimensions are considered herein. The lateral p-n junctions **212** may be arranged in series **1516** in the portion of optical core **1514** facing the light-guiding rib **1509**.

(37) For a lateral p-n junction **212**, a p-type region contains an excess of holes, while an n-type region contains an excess of electrons. At or near the lateral p-n junction **212**, electrons may diffuse across to combine with holes creating a substantial “depletion region” in response to reverse-biasing. FIG. 16 schematically illustrates electrical operation of Si optical phase shifter **100** in FIG. 15, where a first depletion region **310** is formed at lateral p-n junction **212-1**, and a second depletion region **311** is formed at lateral p-n junction **212-3**. The first depletion region **310** and the second depletion region **311** are offset from the lateral center **318** (i.e., along the x-axis) of optical core **1514**. Carrier density variations are responsible for refractive index variations in Si optical waveguide **102**. Thus, the phase of an optical signal propagating through Si optical waveguide **102** may be modulated by changing the carrier densities at the reverse-biased lateral p-n junctions **212**.

(38) In FIG. 17, carrier densities are represented by the width **440** of the depletion regions **310-311** at the lateral p-n junctions **212**. During operation, the width **440** may be adjusted by applying a varying reverse-biasing voltage from a voltage source **450** across the series **1516** of lateral p-n junctions **212**. As is clear from FIG. 17, such biasing also causes p-n junction **212-2** to be forward-biased. Si optical phase shifter **100** further includes biasing electrodes **416-417** configured to electrically couple voltage source **450** across the entire series **1516** of p-n junctions **212** in optical core **1514**. Electrodes **416-417** are located along opposite sides of a segment **430** of optical core **1514**. Electrode **416** is electrically coupled via a heavily p-type doped (p++) portion of a Si slab **1720** to the first p-type region **220**. Electrode **417** is electrically coupled via a heavily n-type doped (n++) portion of a Si slab **1721** to the second n-type region **226**.

(39) FIGS. 18-20 are cross-sectional views of Si optical phase shifter **100** in an illustrative embodiment. The views in FIGS. 18-20 are across a transverse cut plane A-A (e.g., along the x-axis) as shown in FIG. 1. As above, Si optical waveguide **102** of Si optical phase shifter **100** includes lower optical cladding layer **1506**, a Si or hybrid-material optical core **1514** formed by Si layer **1508** and a light-guiding rib **1509**, and upper optical cladding **1510** in the vertical direction along the z-axis. Additional elements of Si optical phase shifter **100** may be incorporated as

desired. Also, FIGS. 18-20 are not drawn to scale.

(40) In FIG. 18, Si optical phase shifter **100** includes a series **1516** of lateral p-n junctions **212** in optical core **1514**. In an embodiment, five lateral p-n junctions **212** (i.e., first, second, third, fourth, and fifth lateral p-n junction **212-1**, **212-2**, **212-3**, **212-4**, and **212-5**) are located in a series **1516** across a width of Si layer **1508**. The lateral p-n junctions **212** are created by doping the crystalline Si material of the Si layer **1508**. The doping creates a first p-type region **520** and a first n-type region **522**, creates a second p-type region **524** and a second n-type region **526**, and creates a third p-type region **528** and a third n-type region **530**. The doping creates three lateral p-n junctions **212-1**, **212-3**, and **212-5** of the same orientation, and two other p-n junctions **212-2** and **212-4** oppositely oriented. Lateral p-n junctions **212-1**, **212-3**, and **212-5** are reverse-biased during operation, and p-n junctions **212-2** and **212-4** are forward-biased during operation, when the entire series **1516** is connected across a suitable DC biasing voltage source. Thus, p-n junctions **212-1**, **212-3**, and **212-5** contribute to modulation when reverse-biased, while p-n junctions **212-2** and **212-4** do not contribute to modulation. Although the series **1516** of lateral p-n junctions **212** includes three lateral p-n junctions **212** of the same p-n orientation in Si layer **1508** shown in FIG. 18, the series **1516** may have more lateral p-n junctions **212** of the same p-n orientation in other embodiments.

(41) FIG. 19 schematically illustrates electrical operation of Si optical phase shifter **100** in FIG. 18, where a first depletion region **610** is formed at lateral p-n junction **212-1**, a second depletion region **611** is formed at lateral p-n junction **212-3**, and a third depletion region **612** is formed at lateral p-n junction **212-5**. The first depletion region **610** and the third depletion region **612** are offset from the lateral center **318** (i.e., along the x-axis) of optical core **1514**, while the second depletion region **611** is generally aligned with the lateral center **318**.

(42) In FIG. 20, carrier densities are represented by the width **440** of the depletion regions **610-612** at the lateral p-n junctions **212**. During operation, the width **440** may be adjusted by applying a varying reverse-biasing voltage from a voltage source **450** across the series **1516** of lateral p-n junctions **212**. As is clear from FIG. 20, such biasing also causes the p-n junctions **212-2** and **212-4** to be forward-biased. Si optical phase shifter **100** further includes biasing electrodes **416-417** configured to electrically couple voltage source **450** across the entire series **1516** of p-n junctions **212** in optical core **1514**. Electrodes **416-417** are located along opposite sides of a segment **430** of Si optical core **208**. Electrode **416** is electrically coupled via a heavily p-type doped (p++) portion of a Si slab **2020** to the first p-type region **520**. Electrode **417** is electrically coupled via a heavily n-type doped (n++) portion of a Si slab **2021** to the third n-type region **530**.

(43) FIG. 21 is a flow chart illustrating a method **2100** of fabricating a Si optical phase shifter in an illustrative embodiment. FIGS. 22-25 illustrate results of the fabrication steps in illustrative embodiments.

(44) Method **2100** includes the step of acquiring or obtaining a Si substrate **104** (step **2102**). In FIG. 22, the Si substrate **104** includes a crystalline Si layer **1508** formed on a lower optical cladding layer **1506**. For example, an SOI wafer **1140** may be acquired having a crystalline Si layer (or device layer) of about 220 nm. In FIG. 21, a portion of the crystalline Si layer **1508** underneath the light-guiding rib **1509** (see FIG. 15) represents the optical core **1514** of the Si optical waveguide **102**. Thus, method **2100** further includes doping the crystalline Si layer **1508** (i.e., the optical core **1514**) to form a plurality of lateral p-n junctions **212** (step **2104**). In FIG. 23, an ion implantation process **1306** or similar process may be performed to create p-type regions and n-type regions in the crystalline Si layer **1508** that form a series of lateral p-n junctions. Although three lateral p-n junctions are illustrated in FIG. 23, more than three lateral p-n junctions may be formed (see FIG. 18).

(45) In FIG. 21, method **2100** further includes forming a light-guiding rib **1509** on the Si layer **1508** (step **2106**). FIG. 24 illustrates a light-guiding rib **1509** formed on the Si layer **1508**. For example, light-guiding rib **1509** may be formed by depositing a Si layer that has a lower refractive

index than the Si layer **1508**, but a higher refractive index than the upper optical cladding **1510**, such as silicon nitride (SiN). In this embodiment, the Si optical waveguide **102** has a geometry of a strip-loaded waveguide with a slab **2422** comprising the optical core **1514**, and the light-guiding rib **1509**. In FIG. **21**, method **2100** further includes forming upper optical cladding **1510** of the Si optical waveguide **102** on the Si layer **1508** and the light-guiding rib **1509** (step **2108**). In FIG. **25**, the upper optical cladding **1510** may be formed by depositing a Si material having a lower refractive index than the Si layer **1508** and the light-guiding rib **1509**, such as silicon dioxide. In FIG. **21**, method **2100** further includes forming a pair of biasing electrodes **416-417** along opposite sides of a segment **430** of the optical core **1514** (step **2110**), as shown in FIG. **20**.

(46) Method **2100** may be performed in multiple areas of a Si substrate **104** to fabricate multiple Si optical phase shifters.

(47) One or more Si optical phase shifters **100** as disclosed above may be used in a variety of optical devices. FIG. **26** illustrates optical devices **2600** that implement one or more Si optical phase shifters **100** in an illustrative embodiment. In general, an optical device **2600** is an apparatus configured to process light or optical waves. Optical device **2600-1**, for example, may comprise a coherent optical module **2612** (e.g., a coherent optical transmitter or a coherent optical transceiver) that implements one or more Si optical phase shifters **100**. Optical device **2600-2**, for example, may comprise an optical modulator **2613** that implements one or more Si optical phase shifters **100** for data modulation of optical carrier(s). An optical modulator **2613** is a type of optical device that manipulates a property of light, such as a radio-frequency traveling wave operated Mach-Zehnder Modulator (MZM), a ring resonator MZM, an optical ring resonator, etc.

(48) As illustrated in FIG. **26**, an Si optical phase shifter **100** may include one or more radio-frequency (RF) traveling-wave electrodes **2630** to operate the Si optical phase shifter **100**.

(49) One or more of optical devices **2600**, or other optical devices, may include or implement a Si MZM. FIG. **27** illustrates an optical device **2700** that implements one or more Si MZMs **2701** in an illustrative embodiment. Although two Si MZMs **2701** are shown in FIG. **27**, more or less Si MZMs **2701** may be implemented in other embodiments.

(50) A Si MZM **2701** includes an optical splitter **2702**, a pair of optical modulation, waveguide arms **2704-2705**, and an optical combiner **2708**. Input power (PIN) from a laser (not shown) is launched into an input port **2710**, and is split at optical splitter **2702** to be shared by optical modulation, waveguide arm **2704** and optical modulation, waveguide arm **2705** (e.g., the power splitting may cause about equal amounts of the light from input port **2710** to be directed to each of the optical modulation arms **2704** and **2705**). One or both of the optical modulation, waveguide arms **2704-2705** has one or more segments therealong that implement(s) a Si optical phase shifter **100** as described above. A negative-bias voltage is applied across a Si optical phase shifter **100** via biasing electrodes (e.g., see FIG. **4**), and an RF modulation signal may be applied across a Si optical phase shifter **100** via one or more RF traveling-wave electrodes **2630** to alter the optical refractive index of the segment and change a phase shift accumulated by the light propagating therethrough. Optical combiner **2708** combines the light from the two optical modulation, waveguide arms **2704-2705**. In the optical combiner **2708**, the light from the optical modulation, waveguide arms **2704-2705** constructively or destructively interferes depending on an accumulated phase difference between the light from the different optical modulation arms **2704-2705**, e.g., to provide amplitude modulation of the output light (P.sub.OUT) at output port **2716**. In embodiments having, e.g., nested pairs of two such MZM optical modulators, output optical combiner **2708** can output light having separate in-phase and quadrature-phase modulation.

(51) One or more of optical devices **2600**, or other optical devices, may include or implement an optical ring resonator or a ring resonator MZM. FIG. **28** illustrates an optical device **2800** that implements one or more optical ring resonators **2801** in an illustrative embodiment. A Si optical phase shifter **100** may be implemented along an optical waveguide segment **2810** of optical ring resonator **2801**.

(52) Although specific embodiments were described herein, the scope of the disclosure is not limited to those specific embodiments. The scope of the disclosure is defined by the following claims and any equivalents thereof.

## Claims

1. An apparatus, comprising: an optical phase shifter comprising: a planar optical waveguide having a silicon optical core and a geometry of a rib waveguide, wherein dimensions of the silicon optical core as the rib waveguide include a rib width and a core thickness; and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core; wherein the segment of the silicon optical core comprises a series of p-n junctions, the series extending in a direction transverse to an optical propagation direction of an optical signal and across the rib width of the silicon optical core in a segment of the planar optical waveguide including the segment of the silicon optical core; wherein at least two of the p-n junctions are configured to be reverse biased by applying a voltage across the biasing electrodes; wherein the optical phase shifter is configured to control a phase of the optical signal propagating through the planar optical waveguide by changing carrier densities at the at least two of the p-n junctions, due to varying the voltage, to alter a refractive index of the planar optical waveguide; wherein the at least two of the p-n junctions comprise two reverse-biased p-n junctions offset from a lateral center of the silicon optical core in the segment thereof, and a single reverse-biased p-n junction aligned with the lateral center.
2. The apparatus of claim 1, wherein at least another of the p-n junctions is located between the two of the p-n junctions and is configured to be forward biased by applying the voltage across the biasing electrodes.
3. The apparatus of claim 1, further comprising at least one radio-frequency traveling-wave electrode to operate the optical phase shifter.
4. The apparatus of claim 1, further comprising a Mach-Zehnder optical modulator having a parallel pair of optical waveguide arms; wherein the optical phase shifter is along one of the optical waveguide arms.
5. The apparatus of claim 4, further comprising at least one radio-frequency traveling-wave electrode configured to operate the optical phase shifter.
6. The apparatus of claim 1, wherein the two reverse-biased p-n junctions are located on opposite sides of the lateral center of the silicon optical core in the segment thereof.
7. The apparatus of claim 1, wherein: the optical phase shifter is formed on a substrate; and the p-n junctions of the silicon optical core are oriented in a vertical direction transverse to the substrate.
8. The apparatus of claim 7, wherein: the optical phase shifter is formed on a silicon-on-insulator wafer having an insulating layer between a silicon layer and the substrate.
9. The apparatus of claim 1, wherein: the planar optical waveguide includes a lower optical cladding layer, the silicon optical core, and an upper optical cladding; and the p-n junctions of the silicon optical core are oriented in a vertical direction between the lower optical cladding layer and the upper optical cladding.
10. The apparatus of claim 1, wherein: the series comprises three of the p-n junctions configured to be reverse biased by applying the voltage across the biasing electrodes.
11. An apparatus, comprising: a Mach-Zehnder optical modulator having a parallel pair of optical waveguide arms; wherein an optical phase shifter is along one of the optical waveguide arms, the optical phase shifter comprising: a planar optical waveguide having a silicon optical core and a geometry of a rib waveguide, wherein dimensions of the silicon optical core as the rib waveguide include a rib width and a core thickness; and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core; wherein the segment of the silicon optical core comprises a series of p-n junctions, the series extending in a direction transverse to an optical propagation direction of an optical signal and across the rib width of the silicon optical core in a

segment of the planar optical waveguide including the segment of the silicon optical core; wherein the series comprises at least three of the p-n junctions configured to be reverse biased by applying a voltage across the biasing electrodes; wherein the optical phase shifter is configured to control a phase of the optical signal propagating through the planar optical waveguide by changing carrier densities at the at least three of the p-n junctions, due to varying the voltage, to alter a refractive index of the planar optical waveguide.

12. The apparatus of claim 11, wherein at least another of the p-n junctions is located between the two of the p-n junctions and is configured to be forward biased by applying the voltage across the biasing electrodes.

13. The apparatus of claim 11, further comprising: at least one radio-frequency traveling-wave electrode configured to operate the optical phase shifter.

14. The apparatus of claim 11, wherein two of the at least three of the p-n junctions are located on opposite sides of the lateral center of the silicon optical core in the segment thereof.

15. The apparatus of claim 11, wherein: the optical phase shifter is formed on a substrate; and the p-n junctions of the silicon optical core are oriented in a vertical direction transverse to the substrate.

16. The apparatus of claim 11, wherein: the planar optical waveguide includes a lower optical cladding layer, the silicon optical core, and an upper optical cladding; and the p-n junctions of the silicon optical core are oriented in a vertical direction between the lower optical cladding layer and the upper optical cladding.

17. An apparatus, comprising: a traveling-wave Mach-Zehnder optical modulator having a parallel pair of optical waveguide arms; wherein an optical phase shifter is along one of the optical waveguide arms, the optical phase shifter comprising: an optical waveguide having a silicon optical core and a geometry of a rib waveguide, wherein dimensions of the silicon optical core as the rib waveguide include a rib width and a core thickness; and a pair of biasing electrodes located along opposite sides of a segment of the silicon optical core; wherein a transverse cross-section of the silicon optical core includes a plurality of p-n junctions in series extending in a direction transverse to an optical propagation direction of an optical signal and across the rib width of the silicon optical core in a segment of the optical waveguide including the segment of the silicon optical core; wherein at least two of the p-n junctions are configured to be reverse biased by applying a voltage across the biasing electrodes; wherein the optical phase shifter is configured to control a phase of the optical signal propagating through the optical waveguide by changing carrier densities at the at least two of the p-n junctions, due to varying the voltage, to alter a refractive index of the optical waveguide; wherein the at least two of the p-n junctions comprise two reverse-biased p-n junctions offset from a lateral center of the silicon optical core in the segment thereof, and a single reverse-biased p-n junction aligned with the lateral center.

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