

PHASE SHIFTER AND METHOD OF FORMING THE SAME**TECHNICAL FIELD**

[0001] Various embodiments of this disclosure may relate to a phase shifter. Various embodiments of this disclosure may relate to a method of forming a phase shifter.

BACKGROUND

[0002] Signal transmission is often accomplished by modulation of an optical carrier signal using electro-optical modulators. This is commonly done using a method of intensity modulation with a Mach Zehnder-based interferometric modulator, which includes an input waveguide, an optical splitter, two optical signal paths where one or both contain a phase-shifting element (i.e. phase shifter), an optical combiner, and an output waveguide. Typically, the intensity of the optical signal at the Mach-Zehnder modulator output is a result of interference effects where the phase of the optical carrier in one path is changed with respect to the other optical path.

[0003] Existing communication networks between the baseband unit and remote radio unit rely on signal transmission in the digital domain as specified by the common public radio interface protocol. An alternative method of signal transmission is to employ an analog optical link. A radio frequency signal, provided by a radio frequency source, is imposed onto the optical carrier signal, provided by an optical source such as a laser and using an electro-optic modulator such as Mach-Zehnder modulator. The modulated optical signal is then transmitted from one location to another by fiber optics network. This method of signal transmission is advantageous compared to currently employed methods to reduce the number of components in the optical link, which translates to reduction in complexity, cost, power consumption. However, analog optical links are limited by non-linear impairments due to the non-linear output response of the

modulator and transmission properties in optical fibers. In order to realize the analog radio over fiber link, the linearity of the modulator would be required to be sufficiently high to prevent significant distortions, the third order intermodulation distortions occurring at frequencies overlapping with the transmitted radio frequencies (RF) of interest.

[0004] The Mach-Zehnder modulator transfer function is inherently non-linear. Hence, proposed approaches to suppress the third order intermodulation signals, i.e., to increase the spurious free dynamic range of the Mach-Zehnder modulator, involve introduction of another source of non-linearity by means of electronic or optical techniques such as applying pre-distortion, employing series/parallel multiple Mach-Zehnder modulator configuration or inherent material non-linear electro-optical effects.

[0005] For example, third order intermodulation suppression can be achieved through two Mach-Zehnder modulators connected in parallel. However, the frequency responses of both Mach-Zehnder modulators are required to be as similar as possible and the input electrical signals to both Mach-Zehnder modulators require precise amplitude and phase relationship, both of which are challenging to realize at scale which will be required for future communication networks.

[0006] Other types of modulators may rely on mechanisms such as Quantum-Confined Stark Effect (QCSE) to achieve signal modulation. QCSE refers to the change in absorption characteristics of quantum well structures when an external electric field is applied. In the context of signal modulation, electro-absorption modulators work by intensity modulation, i.e., 0V gives a '1' state and <0V gives a '0' state. Commonly, QCSE devices contain quantum well layers that are each sandwiched by quantum barrier layers whereby the well material has a bandgap narrower than the barrier material. This can be achieved, for example, using germanium (Ge) and silicon-germanium ($\text{Si}_{1-x}\text{Ge}_x$ or simply SiGe) as the well and barrier layers respectively. However, to form an effective electro-absorptive multiple quantum well device,

the SiGe barrier layer is required to have high concentration of Ge. Furthermore, the QCSE effect relies on the band tilting phenomenon due to applied electric field in the perpendicular direction of pn junction to produce the red shift in absorption spectrum under applied bias.

SUMMARY

[0007] Various embodiments may relate to a phase shifter. The phase shifter may include rib waveguide. The rib waveguide may include a base. The rib waveguide may further include a stacked arrangement on the base, the stacked arrangement including alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). The phase shifter may also include a first slab waveguide region and a second slab waveguide region. A first region of the rib waveguide, the first region of the rib waveguide including a first region of the base and a first region of the stacked arrangement, may be a doped region having a first type conductivity. A second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide including a second region of the base and a second region of the stacked arrangement, may be a doped region having a second type conductivity opposite to the first type conductivity. The first slab waveguide region, the first slab waveguide region adjoining the first region of the base, may be a doped region having the first type conductivity. The second slab waveguide region, the second slab waveguide region adjoining the second region of the base, may be a doped region having the second type conductivity.

[0008] Various embodiments may include a method of forming a phase shifter. The method may include forming a rib waveguide. The rib waveguide may include a base, and a stacked arrangement on the base, the stacked arrangement including alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). The method may also include forming a first slab waveguide region. The method may further include forming a second slab waveguide region. A first region of the rib waveguide, the first region of the rib waveguide including a first region

of the base and a first region of the stacked arrangement, may be a doped region having a first type conductivity. A second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide including a second region of the base and a second region of the stacked arrangement, is a doped region having a second type conductivity opposite to the first type conductivity. The first slab waveguide region, the first slab waveguide region adjoining the first region of the base, may be a doped region having the first type conductivity. The second slab waveguide region, the second slab waveguide region adjoining the second region of the base, may be a doped region having the second type conductivity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1A shows the existing 5G fronthaul network architecture.

FIG. 1B shows the proposed 6G fronthaul network architecture enabled by a high linearity photonic modulator according to various embodiments.

FIG. 1C shows a schematic illustrating the modulator being a non-linear device.

FIG. 1D shows a plot of output power (in decibels-milliwatts or dBm) as a function of input power (in decibels-milliwatts or dBm) illustrating derivation of the spurious free dynamic range (SFDR) according to various embodiments.

FIG. 2 shows a general illustration of a phase shifter according to various embodiments.

FIG. 3A shows a general illustration of a method of forming a phase shifter according to various embodiments.

FIG. 3B shows another illustration of a method of forming a phase shifter according to various embodiments.

FIG. 4A shows a cross-sectional schematic of a phase shifter according to various embodiments.

FIG. 4B shows a modulator in which the phase shifter is arranged along one of the two optical arms of the modulator according to various embodiments.

FIG. 4C shows a cross-sectional schematic of another phase shifter according to various embodiments.

FIG. 4D shows a perspective view of the phase shifter according to various embodiments shown in FIG. 4C.

FIG. 5A shows a top silicon (Si) layer of a silicon-on-insulator (SOI) substrate according to various embodiments.

FIG. 5B shows the silicon (Si) layer after etching according to various embodiments.

FIG. 5C shows the patterning of the silicon oxide layer to form the trench according to various embodiments.

FIG. 5D shows the formation of the stacked arrangement of the rib waveguide according to various embodiments.

FIG. 5E shows the formation of doped regions in the rib waveguide and doped slab waveguide regions according to various embodiments.

FIG. 5F shows forming of the cladding according to various embodiments.

FIG. 5G shows the forming of the electrodes according to various embodiments.

FIG. 6A shows the formation of stack according to various embodiments.

FIG. 6B shows the formation of the photoresist structure according to various embodiments.

FIG. 6C shows the formation of the stacked arrangement according to various embodiments.

FIG. 6D shows the formation of doped regions in the rib waveguide and doped slab waveguide regions according to various embodiments.

FIG. 6E shows forming of the cladding according to various embodiments.

FIG. 6F shows the forming of the electrodes according to various embodiments.

FIG. 7 shows (top) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.9}\text{Ge}_{0.1}$ according to various embodiments; (middle) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.8}\text{Ge}_{0.2}$ according to various embodiments; and (below) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.7}\text{Ge}_{0.3}$ according to various embodiments.

DESCRIPTION

[0010] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0011] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments,

even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0012] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0013] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance, e.g. within 10% of the specified value.

[0014] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0015] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0016] By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0017] Embodiments described in the context of one of the phase shifters or modulators are analogously valid for the other phase shifters or modulators, embodiments described in the context of a method are analogously valid for a phase shifter/modulator, and vice versa.

[0018] The introduction of 6G aims to achieve data rates of 1 Tbps, latency < 0.1 ms, coverage for up to 10^7 devices/km², etc. Currently, 5G severely lags behind due to limitations originating from the fronthaul network architecture used in existing wireless communications network links, i.e. digital radio over fiber (DRoF). An analog radio over fiber fronthaul (ARoF) may be needed to achieve significant improvements to data capacity and latencies. Advantages

of ARoF may include greater data capacity (50x) and lower latency (50x) at reduced costs (7x), power consumption (3x) and footprint (2x).

[0019] As mentioned above, the key enabling component for ARoF may be a high linearity photonic modulator, e.g. with spurious free dynamic range (SFDR) > 130 dBc. Hz^{2/3}. FIG. 1A shows the existing 5G fronthaul network architecture. FIG. 1B shows the proposed 6G fronthaul network architecture enabled by a high linearity photonic modulator according to various embodiments.

[0020] Existing modulators have yet to demonstrate SFDR > 130 dBc. Hz^{2/3}. Photonic (Mach Zehnder or ring architecture) modulators are inherently nonlinear devices. FIG. 1C shows a schematic illustrating the modulator being a non-linear device. As mentioned above, in order to linearize a modulator, one or more non-linear compensation techniques are used: (1) operating two modulators in series or parallel; (2) injecting electronic pre-distortion signals; and/or (3) using a material's inherent electro-optic effects. The disadvantages may come from either requiring identical frequency responses from two devices, complicated device fabrication methods to incorporate III-V/LiNbO₃ on silicon or specific electrical operating conditions governed by complex circuit design.

[0021] In an analog radio over fiber fronthaul (ARoF) communications system, the system linearity may be limited by the SFDR which primarily comes from non-linearities generated by the electro-optics (EO) modulator. The SFDR may be defined as the range between the smallest signal that can be detected (just above noise floor) and the largest distortion-free signal. FIG. 1D shows a plot of output power (in decibels-milliwatts or dBm) as a function of input power (in decibels-milliwatts or dBm) illustrating derivation of the spurious free dynamic range (SFDR) according to various embodiments. Graphically, $SFDR = \frac{2}{3}(OIP_3 - N_0)$ as shown in FIG. 1D.

[0022] Various embodiments may relate to a multi-layered silicon-germanium/silicon ($\text{Si}_x\text{Ge}_{1-x}/\text{Si}$) modulator that can achieve a high SFDR, e.g. $\text{SFDR} > 130 \text{ dBc} \cdot \text{Hz}^{2/3}$. The high SFDR photonic modulator may be the key enabling component for an ARoF link.

[0023] Various embodiments may relate to a phase shifter (alternatively referred to as a phase shifting device or a phase shifter device) for use in one or both optical paths of the Mach-Zehnder modulator to provide a high spurious free dynamic range. Silicon germanium layers may be introduced into the rib waveguides in the Mach Zehnder modulators. Third order intermodulation distortions may be suppressed by non-linear free carrier plasma dispersion effect present in the structure. The structure may demonstrate the ability to achieve spurious free dynamic range of above $130 \text{ dBc} \cdot \text{Hz}^{2/3}$. This may be obtained through tuning of the germanium (Ge) composition, thickness and strain in the waveguide section which alters the free carrier properties including effective conductivity mass, mobility, and dielectric constant.

[0024] Modulation is achieved in Mach Zehnder modulators when the phase change of the propagating optical wave in one optical path results in a net intensity change due to interference effects with the other optical path at the modulator output. The phase changing element may typically be a pn junction, which forms a depletion region of immobile ions and free carriers in the vicinity, in a rib waveguide geometry that confines the optical wave. Hence, the optical wave interacts with free carriers along the length of the phase shifter. The refractive index (and hence the phase of the optical wave) is tuned by changing the number of free carriers interacting with the optical wave which can be achieved through applying a voltage bias to the phase shifter. More formally, the change in refractive index, Δn , is related to the number free carriers and their conductivity effect masses as expressed by the Drude model:

$$\Delta n = -\frac{e^2 \lambda^2}{8\pi^2 c^2 \epsilon_0 n} \left(\frac{\Delta N_e}{m_{ce}^*} + \frac{\Delta N_h}{m_{ch}^*} \right) \quad (1)$$

where e is the elementary charge, λ is the wavelength of light, c is the speed of light in vacuum, ϵ_0 is the vacuum permittivity, n is the refractive index, ΔN_e is the change in free electron

concentration, ΔN_h is the change in free hole concentration, m_{ce}^* is the conductivity effective mass of electrons and m_{ch}^* is the conductivity effective mass of holes.

[0025] It is apparent that the change in refractive index may be inversely proportional to the conductivity effective masses. The conductivity effective masses can be tuned by strain engineering. For example, growth of SiGe on Si produces a strained SiGe film due to the lattice constant mismatch between SiGe and Si, since the lattice constant of Ge is larger than Si by 4%. Strain effects alter the conductivity effective masses in SiGe because of valence band splitting, where the heavy hole band shifts to an energy level above light hole band, giving rise to a reduced conductivity effective mass. The thickness of SiGe film on Si should be kept below the critical thickness limit to maintain the strain profile.

[0026] Various embodiments may relate to a phase shifter including a stacked arrangement of alternating layers of SiGe and Si, which produces a specific refractive index change profile in the waveguide region to enhance the free carrier effects by tuning the Ge composition and layer thicknesses while maintaining strain in each layer. Furthermore, the phase shifter is based on reverse biased depletion structure. Hence, the pn junction may be created at the center of the waveguide with the electrodes (on two far ends of the slab waveguide) which produce an electric field that is parallel to the transverse direction of the SiGe/Si stack in the rib waveguide structure.

[0027] FIG. 2 shows a general illustration of a phase shifter according to various embodiments. The phase shifter may include rib waveguide 202. The rib waveguide 202 may include a base 204. The rib waveguide 202 may further include a stacked arrangement 206 on the base 204, the stacked arrangement 206 including alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). The phase shifter may also include a first slab waveguide region 208a and a second slab waveguide region 208b. A first region of the rib waveguide 202, the first region of the rib waveguide 202 including a first region 204a of the base 204 and a first

region 206a of the stacked arrangement 206, may be a doped region having a first type conductivity. A second region of the rib waveguide 202 adjoining the first region of the rib waveguide 202, the second region of the rib waveguide 202 including a second region 204b of the base 204 and a second region 206b of the stacked arrangement 206, may be a doped region having a second type conductivity opposite to the first type conductivity. The first slab waveguide region 208a, the first slab waveguide region 208a adjoining the first region 204a of the base 204, may be a doped region having the first type conductivity. The second slab waveguide region 208b, the second slab waveguide region 208b adjoining the second region 204b of the base 204, may be a doped region having the second type conductivity.

[0028] In other words, the phase shifter may include a rib waveguide 202 which two lateral regions having opposite type conductivities. The phase shifter may include a first slab waveguide region 208a adjoining a first lateral region of the rib waveguide 202 and having the same type conductivity as the first lateral region of the rib waveguide 202, as well as a second slab waveguide region 208b adjoining a second lateral region of the rib waveguide 202 and having the same type conductivity as the second lateral region of the rib waveguide 202.

[0029] For avoidance of doubt, FIG. 2 serves to illustrate some features of the phase shifter according to various embodiments, and does not seek to limit the dimensions, aspects ratios, shapes etc. of these features.

[0030] The stacked arrangement 206 may be a vertical stacked arrangement, and as mentioned above, may include alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). For instance, the stacked arrangement 206 may include a first SiGe layer on the base 204, a first Si layer on the first SiGe layer, a second SiGe layer on the first Si layer, a second Si layer on the second SiGe layer and so on. The base 204 may include silicon. In various embodiments, the base 204 may be formed from the silicon layer of a silicon-on-insulator (SOI) substrate. A width of the stacked arrangement 206 may be smaller than a width of the base 204.

[0031] Each SiGe layer may be strained due to the presence of the adjoining Si layers. In various embodiments, a percentage composition of germanium in the layers of silicon-germanium (SiGe) is selected from a range from 5% to 40%. Less germanium may be used as compared to conventional Quantum-Confined Stark Effect-based (QCSE) modulators. For these conventional modulators which are based on electro-absorptive effects, quantum barrier layers may be more than 70% germanium while pure Ge (or higher percentage concentration of germanium than percentage concentration of germanium used in the quantum barrier layers) may be used as strained quantum well layers.

[0032] In various embodiments, the layers of silicon-germanium (SiGe) may have a same percentage composition of germanium. In various other embodiments, the layers of silicon-germanium (SiGe) may have different percentage compositions of germanium. The percentage composition of germanium in a silicon-germanium layer may be provided by $\text{Si}_{1-x}\text{Ge}_x$, where x indicates the ratio of germanium. For instance, a silicon-germanium layer with 40% germanium may be indicated by $\text{Si}_{0.6}\text{Ge}_{0.4}$.

[0033] Each layer of the layers of silicon-germanium (SiGe) may have a thickness below a critical thickness limit so that it remains strained. The critical thickness limit may be dependent on the germanium percentage concentration, for example the critical thickness of SiGe with 30% germanium is approximately 60 nm before strain relaxation sets in. For instance, each layer of the layers of silicon-germanium (SiGe) may have a thickness selected from a range of between 5 nm to 40 nm (inclusive of both end values).

[0034] In various embodiments, each layer of the layers of silicon (Si) may have a thickness selected from a range from 5 nm to 40 nm.

[0035] In various embodiments, the phase shifter may include a first electrode in electrical connection with the first slab waveguide region 208a. In various embodiments, the phase shifter may include a second electrode in electrical connection with the second slab waveguide region

208b. In various embodiments, the phase shifter may be configured such that a voltage difference applied between the first electrode and the second electrode induces an electric field substantially parallel to a transverse direction of the stacked arrangement.

[0036] In various embodiments, the first electrode and/or the second electrode may include any suitable conductive material, e.g. a metal such as aluminum.

[0037] In various embodiments, the phase shifter may include a cladding such that the first electrode extends through the cladding to be in contact with the first slab waveguide region 208a, and the second electrode extends through the cladding to be in contact with the second slab waveguide region 208b. The cladding may include any suitable dielectric such as silicon oxide.

[0038] In various embodiments, the first region of the rib waveguide (i.e. the first region 204a of the base 204 and the first region 206a of the stacked arrangement 206) may have a doping concentration selected from a range from $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$. The second region of the rib waveguide (i.e. the second region 204b of the base 204 and the second region 206b of the stacked arrangement 206) may have a doping concentration selected from a range from $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$. The second region of the rib waveguide may be lateral to the first region of the rib waveguide. The second region 204b of the base 204 may be lateral to the first region 204a of the base 204. Correspondingly, the second region 206b of the stacked arrangement 206 may be lateral to the first region 206a of the stacked arrangement 206.

[0039] In various embodiments, the first slab waveguide region 208a may have a doping concentration selected from a range from $1 \times 10^{19} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$. The second slab waveguide region 208b may have a doping concentration selected from a range from $1 \times 10^{19} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$. The first slab waveguide region 208a may be lateral to the first region of the base 204a. The second slab waveguide region 208b may be lateral to the second region of the base 204b.

[0040] In various embodiments, the first type conductivity may be n-type and the second type conductivity may be p-type. In various other embodiments, the first type conductivity may be p-type and the second type conductivity may be n-type.

[0041] In various embodiments, p-type conductivity may be caused by introducing dopants such as boron, aluminum, and/or gallium, while n-type conductivity may be caused by introducing dopants such as phosphorus, arsenic and/or antimony.

[0042] In various embodiments, a thickness of the first slab waveguide region 208a and/or the second slab waveguide region 208b may be selected from a range from 50 nm to 150 nm, e.g. 70 nm.

[0043] In various embodiments, a thickness of the first slab waveguide region 208a may be equal to or greater than a thickness of the base 204. Likewise, a thickness of the second slab waveguide region 208b may be equal to or greater than a thickness of the base 204.

[0044] In various embodiments, a width of the stacked arrangement may be selected from a range from 400 nm to 600 nm, e.g. 500 nm.

[0045] The phase shifter may be configured to operate in reverse bias. During operation, a depletion region may be formed which extends substantially perpendicularly to the stack arrangement direction or extends substantially perpendicularly to the transverse direction along the layers of Si and SiGe in the rib waveguide structure. The electric field may be in parallel with the stack arrangement transverse direction or the transverse direction along the layers of Si and SiGe in the rib waveguide structure. The electric field direction and the direction of the dopant interface are denoted in FIG. 2.

[0046] Various embodiments may relate to a modulator including a phase shifter as described herein. Various embodiments may include a Mach-Zehnder modulator including a first arm (for providing a first optical path) and a second arm (for providing a second optical path). The Mach-Zehnder modulator may include a phase shifter in one or both arms. The phase

shifter(s) may cause a phase shift between light traveling through the first arm and the second arm.

[0047] Various embodiments may provide a modulator with a spurious free dynamic range (SFDR) $> 130 \text{ dBc} \cdot \text{Hz}^{2/3}$ for enabling analog radio over fiber fronthaul (ARoF) link.

[0048] Various embodiments may operate using the electro-optic mechanism (free carrier plasma dispersion or FCPD). The free carrier plasma dispersion may tune the refractive index by changing the free carrier concentration in the rib waveguide structure. This may provide phase modulation (slowing of the optical wave) which results in optical intensity change at the modulator output due to optical interference effects. In other words, a change in the potential difference applied between the first electrode and the second electrode of the phase shifter may change the free carrier concentration in the rib waveguide, thereby changing the refractive index. The change in refractive index may change the phase of the optical wave passing through the phase shifter present in an optical arm of a modulator, thereby changing an intensity of an resultant optical wave at an output of the modulator due to interference between the optical wave passing through the phase shifter in the optical arm and another optical wave passing through another optical arm of the modulator.

[0049] Conventional modulators using FCPD effect have been explored for high linearity applications with limited success for the past 20 years. The available parameters may mainly be the waveguide geometry, doping concentration and doping interface. By introducing a Si/SiGe stacked arrangement including multiple layers of Si and SiGe, additional tuning knobs (e.g. SiGe composition, thicknesses of the SiGe layers and Si layers, number of layers, strain etc) may be included in the modulator design to manipulate the refractive index change profile. The composition, layer thicknesses, number of layers may be non-trivial to optimize and may require significant simulation time to explore the large design parameter space.

[0050] FIG. 3A shows a general illustration of a method of forming a phase shifter according to various embodiments. The method may include, in 302, forming a rib waveguide. The rib waveguide may include a base, and a stacked arrangement on the base, the stacked arrangement including alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). The method may also include, in 304, forming a first slab waveguide region. The method may further include, in 306, forming a second slab waveguide region. A first region of the rib waveguide, the first region of the rib waveguide including a first region of the base and a first region of the stacked arrangement, may be a doped region having a first type conductivity. A second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide including a second region of the base and a second region of the stacked arrangement, is a doped region having a second type conductivity opposite to the first type conductivity. The first slab waveguide region, the first slab waveguide region adjoining the first region of the base, may be a doped region having the first type conductivity. The second slab waveguide region, the second slab waveguide region adjoining the second region of the base, may be a doped region having the second type conductivity.

[0051] Various embodiments may relate to a method of forming a phase shifter as described herein. For avoidance of doubt, the various steps shown in FIG. 3A are not intended to be in sequence. Exemplary processing sequences would be illustrated below.

[0052] In various embodiments, forming the stacked arrangement may include forming a mask on a substrate, and alternating depositing silicon-germanium (SiGe) and silicon (Si) over a portion of the substrate exposed by the mask before removing the mask. There may be blanket deposition of the SiGe and Si over the substrate and the mask. However, with the removal of the mask, only the portion of the SiGe layers and the Si layers that is over the exposed portion of the substrate may remain, while the remaining portions of the SiGe layers and the Si layers over the mask may be removed together with the mask.

[0053] In various other embodiments, forming the stacked arrangement may include alternating depositing silicon-germanium (SiGe) and silicon (Si) on a substrate to form the alternate layers of silicon-germanium (SiGe) and silicon (Si), forming a mask over the alternate layers of silicon-germanium (SiGe) and silicon (Si), and removing portions of the alternate layers of alternate layers of silicon-germanium (SiGe) and silicon (Si) exposed through the mask.

[0054] Depositing the alternate layers of silicon-germanium (SiGe) and silicon (Si) may be carried out via a suitable deposition method such as chemical vapor deposition (CVD).

[0055] Prior to forming the stacked arrangement, the substrate, e.g. a silicon-on-insulator (SOI) substrate, may be etched so that a portion of the topmost silicon layer is removed to form the slab waveguide regions and the base of the rib waveguide. The etching may be carried out via dry etching, wet etching or a combination of dry etching and wet etching. An initial thickness of the silicon layer may be selected from a range from 100 nm to 300 nm, e.g. 220 nm. After etching, a thickness of the silicon layer (i.e. corresponding to an intended thickness of the first slab waveguide region and/or the second slab waveguide region) may be selected from a range from 50 nm to 150 nm, e.g. 70 nm.

[0056] In various embodiments, a thickness of the first slab waveguide region may be equal to or greater than a thickness of the base. Likewise, a thickness of the second slab waveguide region may be equal to or greater than a thickness of the base.

[0057] After forming the stacked arrangement, the first region of the rib waveguide, the second region of the rib waveguide, the first slab waveguide region and the second slab waveguide region may be implanted with dopants via separate steps (i.e. via separate ion implantation and masking steps). At least 4 implantation steps may be required to form the pn junction in the phase shifter.

[0058] In various embodiments, forming the first region of the rib waveguide, the second region of the rib waveguide, the first slab waveguide region and the second slab waveguide region may include annealing to activate the implanted dopants.

[0059] In various embodiments, the method may also include forming a first electrode in electrical connection with the first slab waveguide region. In various embodiments, the method may further include forming a second electrode in electrical connection with the second slab waveguide region.

[0060] In various embodiments, the method may include forming a cladding. In various embodiments, the first electrode, the second electrode and the cladding may be formed after ion implantation. A dielectric such as silicon oxide may be deposited over the rib waveguide, the first slab waveguide region and the second slab waveguide region to forming a cladding. Portions of the cladding may be removed to form trenches (a first trench extending to the first slab waveguide region and a second trench extending to the second slab waveguide region), and a suitable electrically conductive material such as aluminum may be deposited in the trenches to form the first electrode and the second electrode.

[0061] FIG. 3B shows another illustration of a method of forming a phase shifter according to various embodiments. The method may include, in 352, forming a slab waveguide. The method may further include, in 354, depositing a stack of SiGe/Si layers to form a rib waveguide section. The method may include, in 356, performing ion implantation to form at least 4 regions of different conductivity types and doping concentrations. The method may also include, in 358, annealing the structure. The method may additionally include, in 360, depositing the metal electrodes.

[0062] FIG. 4A shows a cross-sectional schematic of a phase shifter 400 according to various embodiments. FIG. 4B shows a modulator in which the phase shifter 400 is arranged along one of the two optical arms of the modulator according to various embodiments. The two

optical arms may be located at a distance from an optical source 450. FIG. 4A corresponds to line A-A illustrated in FIG. 4B. The phase shifter 400 may include rib waveguide 402 (alternatively referred as rib waveguide section). The rib waveguide 402 may include or consist of a base 404 and a stacked arrangement 406 on the base 404, the stacked arrangement 406 including or consisting of alternate layers of silicon (Si) and layers of silicon-germanium (SiGe). The phase shifter may also include a first slab waveguide region 408a and a second slab waveguide region 408b. A first region of the rib waveguide 402, the first region of the rib waveguide 402 including or consisting of a first region 404a of the base 404 and a first region 406a of the stacked arrangement 406, may be a doped region having a first type conductivity. A second region of the rib waveguide 402 adjoining (and lateral to) the first region of the rib waveguide 402, the second region of the rib waveguide 402 including or consisting of a second region 404b of the base 404 and a second region 406b of the stacked arrangement 406, may be a doped region having a second type conductivity opposite the first type conductivity. The first slab waveguide region 408a, the first slab waveguide region 408a adjoining (and lateral to) the first region 404a of the base 404, may be a doped region having the first type conductivity. The second slab waveguide region 408b, the second slab waveguide region 408b adjoining (and lateral to) the second region 404b of the base 404, may be a doped region having the second type conductivity. The phase shifter 400 may also include a first electrode 410a in electrical connection with the first slab waveguide region 408a, and a second electrode 410b in electrical connection with the second slab waveguide region 408b. The phase shifter may additionally include a cladding 412 such that the first electrode 410a extends through the cladding 412 to be in ohmic contact with the first slab waveguide region 408a, and the second electrode 410b extends through the cladding 412 to be in ohmic contact with the second slab waveguide region 408b.

[0063] During operation, optical signals at wavelengths near 1310 nm or 1550 nm which are suitable for communication applications may propagate in the rib waveguide 402. The optical signals may be emitted or generated by the optical source 450.

[0064] The germanium (Ge) composition may be between 5% to 40% (inclusive of both end values). In various embodiments, the percentage compositions of Ge may be varied across different SiGe layers, while in various other embodiments, the SiGe layers may have the same percentage composition of Ge. The thickness of each SiGe layer may be required to be within the critical thickness limit to avoid strain relaxation. In various embodiments, the thickness of each SiGe layer may be between 5 nm to 40 nm (inclusive of both end values). The thickness of each Si layer may be between 5 nm to 40 nm (inclusive of both end values). The number of periods of alternate Si and SiGe layers may vary between 2 to 9 periods (inclusive of both end values).

[0065] As mentioned above, the rib waveguide 402 may contain a first doped region (including a first region 404a of the base 404 and a first region 406a of the stacked arrangement 406) with a certain type conductivity, such as p-type, and a second doped region (including a second region 404b of the base 404 and a second region 406b of the stacked arrangement 406) with another type conductivity, such as n-type. The doping concentrations in the rib waveguide may be between $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$ (inclusive of both end values). The dopant interface may substantially be perpendicular to the plane of Si/SiGe stack.

[0066] The slab waveguide regions 408a, 408b (providing ohmic contact to electrodes 410a, 410b) may each be the same type of conductivity as the adjacent doped region of the rib waveguide 402. The doping concentrations of these slab waveguide regions 408a, 408b may be between $1 \times 10^{19} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$ (inclusive of both end values). The dopings may be contributed by dopants such as boron, aluminum, and/or gallium for p-type, and phosphorus, arsenic, and/or antimony for n-type.

[0067] The phase shifter 400 may be operated under reverse bias voltage. The bias voltage signal and radio frequency modulation signal may be applied at the electrodes 410a, 410b which form the cathode nearer to a n-type slab waveguide region, and anode nearer to a p-type slab waveguide region. The applied electric field may be parallel to the transverse direction of the Si/SiGe stack in the rib waveguide structure.

[0068] FIG. 4C shows a cross-sectional schematic of another phase shifter 400' according to various embodiments. The phase shifter 400' has similar features as phase shifter 400 shown in FIG. 4A, and corresponding features are labelled with the same reference number. The slab waveguide regions 408a, 408b of phase shifter 400' may be thicker than the base 404. The phase shifter 400' may also include a further silicon layer having a region 404c of the first type conductivity and a region 404d of the second type conductivity on the stacked arrangement 406.

[0069] FIG. 4D shows a perspective view of the phase shifter 400' according to various embodiments shown in FIG. 4C. Corresponding features are labelled with the same reference number.

[0070] FIGS. 5A-G illustrate a method of fabricating the phase shifter according to various embodiments. FIG. 5A shows a top silicon (Si) layer 514 of a silicon-on-insulator (SOI) substrate according to various embodiments. The initial thickness of the silicon layer 514 of the SOI substrate may be of any value from 100 nm to 300 nm, e.g. 220 nm. The silicon layer 514 may be first etched to the intended slab waveguide thickness. The intended slab waveguide thickness may be of any value from 50 nm to 150 nm, e.g. 70 nm. The etching may be dry etching, wet etching or a combination of wet etching and dry etching to achieve a smooth surface suitable for deposition. FIG. 5B shows the silicon (Si) layer 514' after etching according to various embodiments. FIG. 5C shows the patterning of the silicon oxide layer 516 to form the trench 518 according to various embodiments. Silicon oxide may be deposited onto the etched Si layer 514' to form a silicon oxide layer 516. A trench 518 may be subsequently etched

onto the silicon oxide layer 516 using photoresist for pattern definition. The photoresist may be removed at this point.

[0071] FIG. 5D shows the formation of the stacked arrangement 506 of the rib waveguide according to various embodiments. The silicon oxide layer 516 with the trench 518 may be used as a mask. A silicon-germanium (SiGe) layer may be deposited directly in the trench 518 onto the exposed Si layer 514'. Once the SiGe layer is of sufficient thickness, a Si layer may be deposited. The alternating SiGe and Si deposition steps may be performed until a sufficient thickness is achieved to form the stacked arrangement 506 of the rib waveguide. There may be blanket deposition of the SiGe and Si over the silicon oxide layer 516 and the mask. However, with the removal of the mask, only the portion of the SiGe layers and the Si layers that is over the exposed portion of the silicon layer 514' may remain, while the remaining portions of the SiGe layers and the Si layers over the mask may be removed together with the mask. Accordingly, the width of the trench may define the width of the stacked arrangement 506. The width of the stacked arrangement 506 may be between 400 nm to 600 nm (inclusive of both end values), e.g. 500 nm. The surrounding silicon oxide layer 516 may now be removed.

[0072] FIG. 5E shows the formation of doped regions in the rib waveguide and doped slab waveguide regions according to various embodiments. Ion implantation may be used to form the doped regions in the rib waveguide and to form doped slab waveguide regions. Each region of different conductivities and doping concentrations may first be defined using photoresist as masking layer, and ion implantation using suitable conditions may then be carried out. A minimum of four of such steps is required to form the following four regions: (i) a first region of the rib waveguide including a first region 506a of the stacked arrangement 506 and a first region 504a of the base 504; (ii) a second region of the rib waveguide including a second region 506b of the stacked arrangement 506 and a second region 504b of the base 504; (iii) a first slab waveguide region 508a; and (iv) a second slab waveguide region 508b. An annealing step is

used to activate the implanted dopants. Any remaining oxide or photoresist may be removed after the ion implantation step. A cladding 512 (also referred to as upper cladding layer) of silicon oxide may then be deposited. FIG. 5F shows forming of the cladding 512 according to various embodiments.

[0073] FIG. 5G shows the forming of the electrodes 510a, 510b according to various embodiments. In order to form the electrodes 510a, 510b, trenches may be etched into the cladding 512 until reaching the first slab waveguide region 508a and the second slab waveguide region 508b, and a metal such as aluminum may be deposited into the trenches to form the electrodes 510a, 510b.

[0074] FIGS. 6A-F illustrate a method of fabricating the phase shifter according to various other embodiments. Alternatively, as shown in FIG. 6A, after the step shown in FIG. 5B, a silicon-germanium (SiGe) layer may be deposited directly onto the exposed Si layer 614' (corresponding to Si layer 514' shown in FIG. 5B). Once the SiGe layer is of sufficient thickness, a Si layer may be deposited. The alternating SiGe and Si deposition steps may be performed until a sufficient thickness is achieved, thereby forming stack 606'. FIG. 6A shows the formation of stack 606' according to various embodiments.

[0075] Thereafter, photoresist and/or hard mask material such as silicon dioxide or silicon nitride may be deposited onto stack 606', thereby forming masking structure 616 (alternatively referred to as mask) to define the etching region. FIG. 6B shows the formation of the masking structure 616 according to various embodiments. An etching process may be subsequently used to form the stacked arrangement 606 as shown in FIG. 6C. FIG. 6C shows the formation of the stacked arrangement 606 according to various embodiments. The etching process may involve wet etching, dry etching or a combination of wet etching and dry etching.

[0076] FIG. 6D shows the formation of doped regions in the rib waveguide and doped slab waveguide regions according to various embodiments. Ion implantation may be used to form

the doped regions in the rib waveguide and to form doped slab waveguide regions. Each region of different conductivities and doping concentrations may first be defined using photoresist as masking layer, and ion implantation using suitable conditions may then be carried out. A minimum of four of such steps is required to form the following four regions: (i) a first region of the rib waveguide including a first region 606a of the stacked arrangement 606 and a first region 604a of the base 604; (ii) a second region of the rib waveguide including a second region 606b of the stacked arrangement 606 and a second region 604b of the base 604; (iii) a first slab waveguide region 608a; and (iv) a second slab waveguide region 608b. An annealing step may then be used to activate the implanted dopants. Any remaining oxide or photoresist may be removed after the ion implantation step.

[0077] In various embodiments, it may also be envisioned that the ion implantation and annealing steps may be carried out before the patterning steps as shown in FIGS. 6B-C. The portions of the stack 606' over the portions of the silicon layer 614' used to define slab waveguide regions 608a and 608b may be implanted with ions of the same type conductivity as that used for doping slab waveguide regions 608a and 608b, respectively. These portions of the stack 606' over slab waveguide regions 608a and 608b may subsequently be etched away as shown in FIGS. 6B-C.

[0078] A cladding 612 (also referred to as upper cladding layer) of silicon oxide may then be deposited. FIG. 6E shows forming of the cladding 612 according to various embodiments.

[0079] FIG. 6F shows the forming of the electrodes 610a, 610b according to various embodiments. In order to form the electrodes 610a, 610b, trenches may be etched into the cladding 612 until reaching the silicon layer 614', and a metal such as aluminum may be deposited into the trenches to form the electrodes 610a, 610b.

[0080] Simulation results are presented in FIG. 7. FIG. 7 shows (top) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free

dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.9}\text{Ge}_{0.1}$ according to various embodiments; (middle) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.8}\text{Ge}_{0.2}$ according to various embodiments; and (below) a plot of thickness (in nanometers or nm) as a function of number of periods illustrating the variation of spurious free dynamic range (SFDR) (decibels relative to carrier Hertz to power of two-thirds or dBc. $\text{Hz}^{2/3}$) for $\text{Si}_{0.7}\text{Ge}_{0.3}$ according to various embodiments. As indicated in FIG. 7, each plot may represent a structure of a particular Ge composition. The largest spurious free dynamic range obtained for each Ge composition at 10%, 20% and 30% are 132.4 dBc. $\text{Hz}^{2/3}$, 143.5 dBc. $\text{Hz}^{2/3}$ and 133.3 dBc. $\text{Hz}^{2/3}$ respectively, interestingly for 5 periods, 15 nm thick SiGe and Si. It is demonstrated that a number of design variation may achieve SFDR > 130 dBc. $\text{Hz}^{2/3}$ and the best simulated SFDR is 143.5 dBc. $\text{Hz}^{2/3}$. The design space is large and may be constrained by number of periods of Si/Si_{1-x}Ge_x, thickness of Si_{1-x}Ge_x layers, composition of Si_{1-x}Ge_x, and phase shifter length.

CLAIMS

1. A phase shifter comprising:
 - a rib waveguide comprising:
 - a base; and
 - a stacked arrangement on the base, the stacked arrangement comprising alternate layers of silicon (Si) and layers of silicon-germanium (SiGe);
 - a first slab waveguide region; and
 - a second slab waveguide region;

wherein a first region of the rib waveguide, the first region of the rib waveguide comprising a first region of the base and a first region of the stacked arrangement, is a doped region having a first type conductivity;

wherein a second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide comprising a second region of the base and a second region of the stacked arrangement, is a doped region having a second type conductivity opposite to the first type conductivity;

wherein the first slab waveguide region, the first slab waveguide region adjoining the first region of the base, is a doped region having the first type conductivity; and

wherein the second slab waveguide region, the second slab waveguide region adjoining the second region of the base, is a doped region having the second type conductivity.
2. The phase shifter according to claim 1,
 - wherein a percentage composition of germanium in the layers of silicon-germanium (SiGe) is selected from a range from 5% to 40%.
3. The phase shifter according to claim 1,
 - wherein the layers of silicon-germanium (SiGe) have a same percentage composition of germanium.
4. The phase shifter according to claim 1,

wherein the layers of silicon-germanium (SiGe) have different percentage compositions of germanium.

5. The phase shifter according to claim 1,
wherein each layer of the layers of silicon-germanium (SiGe) has a thickness selected from a range from 5 nm to 40 nm.
6. The phase shifter according to claim 1,
wherein each layer of the layers of silicon (Si) has a thickness selected from a range from 5 nm to 40 nm.
7. The phase shifter according to claim 1,
wherein the first region of the rib waveguide has a doping concentration selected from a range from $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$; and
wherein the second region of the rib waveguide has a doping concentration selected from a range from $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$.
8. The phase shifter according to claim 1,
wherein the first slab waveguide region has a doping concentration selected from a range from $1 \times 10^{19} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$; and
wherein the second slab waveguide region has a doping concentration selected from a range from $1 \times 10^{19} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$.
9. The phase shifter according to claim 1,
wherein the first type conductivity is n-type and the second type conductivity is p-type.
10. The phase shifter according to claim 1,
wherein a thickness of the first slab waveguide region or the second slab waveguide region is selected from a range from 50 nm to 150 nm.
11. The phase shifter according to claim 1,

wherein a width of the stacked arrangement is selected from a range from 400 nm to 600 nm.

12. The phase shifter according to claim 1,

wherein the first slab waveguide region is lateral to the first region of the base; and
wherein the second slab waveguide region is lateral to the second region of the base.

13. The phase shifter according to claim 1, further comprising:

a first electrode in electrical connection with the first slab waveguide region; and
a second electrode in electrical connection with the second slab waveguide region;
wherein the phase shifter is configured such that a voltage difference applied
between the first electrode and the second electrode induces an electric field
substantially parallel to a transverse direction of the stacked arrangement.

14. A Mach-Zehnder modulator comprising:

a first arm for providing a first optical path, the first arm comprising a phase shifter;
and
a second arm for providing a second optical path;
wherein the phase shifter causes a phase shift between light traveling through the
first arm and the second arm;
wherein the phase shifter comprises:

a rib waveguide comprising:

a base; and

a stacked arrangement on the base, the stacked arrangement
comprising alternate layers of silicon (Si) and layers of silicon-
germanium (SiGe);

a first slab waveguide region; and

a second slab waveguide region;

wherein a first region of the rib waveguide, the first region of the rib waveguide
comprising a first region of the base and a first region of the stacked arrangement, is
a doped region having a first type conductivity;

wherein a second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide comprising a second region of the base and a second region of the stacked arrangement, is a doped region having a second type conductivity opposite to the first type conductivity;

wherein the first slab waveguide region, the first slab waveguide region adjoining the first region of the base, is a doped region having the first type conductivity; and

wherein the second slab waveguide region, the second slab waveguide region adjoining the second region of the base, is a doped region having the second type conductivity.

15. A method of forming a phase shifter, the method comprising:

forming a rib waveguide comprising:

a base; and

a stacked arrangement on the base, the stacked arrangement comprising alternate layers of silicon (Si) and layers of silicon-germanium (SiGe);

forming a first slab waveguide region; and

forming a second slab waveguide region;

wherein a first region of the rib waveguide, the first region of the rib waveguide comprising a first region of the base and a first region of the stacked arrangement, is a doped region having a first type conductivity;

wherein a second region of the rib waveguide adjoining the first region of the rib waveguide, the second region of the rib waveguide comprising a second region of the base and a second region of the stacked arrangement, is a doped region having a second type conductivity opposite to the first type conductivity;

wherein the first slab waveguide region, the first slab waveguide region adjoining the first region of the base, is a doped region having the first type conductivity; and

wherein the second slab waveguide region, the second slab waveguide region adjoining the second region of the base, is a doped region having the second type conductivity.

16. The method according to claim 15,

wherein forming the stacked arrangement comprises:

forming a mask on a substrate, and

alternating depositing silicon-germanium (SiGe) and silicon (Si) over a portion of the substrate exposed by the mask before removing the mask.

17. The method according to claim 15,

wherein forming the stacked arrangement comprises:

alternating depositing silicon-germanium (SiGe) and silicon (Si) on a substrate to form the alternate layers of silicon-germanium (SiGe) and silicon (Si);

forming a mask over the alternate layers of silicon-germanium (SiGe) and silicon (Si); and

removing portions of the alternate layers of alternate layers of silicon-germanium (SiGe) and silicon (Si) exposed through the mask.

18. The method according to claim 15,

wherein the first region of the rib waveguide, the second region of the rib waveguide, the first slab waveguide region and the second slab waveguide region are implanted with dopants via separate steps.

19. The method according to claim 18,

wherein forming the first region of the rib waveguide, the second region of the rib waveguide, the first slab waveguide region and the second slab waveguide region comprise annealing to activate the implanted dopants.

20. The method according to claim 15, the method further comprising:

forming a first electrode in electrical connection with the first slab waveguide region;

and

forming a second electrode in electrical connection with the second slab waveguide region.