

Specification
Optical Modulator

Technical Field

5 [0001] The present invention relates to a charge-accumulation-type optical modulator using a MOS structure consisting of compound semiconductors.

Background Art

[0002] Technology of integrating compound
10 semiconductor elements on a silicon-on-insulator (SOI) substrate utilized as a communication optical device is attracting more attention. Particularly, technology of integrating a laser and an optical modulator is important as to dramatically increase integration
15 density of communication devices and to reduce the cost. For an optical modulator that needs higher speed and efficiency, a charge-accumulation-type optical modulator with a MOS structure including an n-type InP layer and a p-type Si layer with little optical loss has potential
20 to achieve those needs (see non-patent literature 1).

[0003] As shown in Fig. 4, this optical modulator is formed from a p-type silicon layer 402 formed on a buried insulating layer 401, an insulating layer 403 formed on the p-type silicon layer 402, and an n-type
25 InP layer 404 formed on the insulating layer 403. A p-electrode 405 is connected to the p-type silicon layer 402, and an n-electrode 406 is connected to the n-type

InP layer 404. The buried insulating layer 401 functions as a clad. The p-type silicon layer 402 is formed by patterning an SOI layer 411 on the buried insulating layer 401. An air groove 412 is formed in a side portion of the p-type silicon layer 402 on the formation side of the n-electrode 406 with the SOI layer 411. The upper surface of the n-type InP layer 404, which is not covered with the n-electrode 406, is open to a space.

10 [0004] Part of the p-type silicon layer 402 and part of the n-type InP layer 404 are arranged so as to overlap each other in a planar view, and form an optical waveguide portion where light to be modulated is guided. In this optical waveguide portion, the insulating layer 15 403 is sandwiched between the p-type silicon layer 402 and the n-type InP layer 404 in a stacking direction. Light to be modulated is confined in a light confinement portion including clad regions consisting of buried insulating layer 401, the air groove 412, an upper 20 space, and the like, thereby forming a waveguide mode 421.

[0005] In this optical modulator, by modulating the concentration of majority carriers accumulated at the interfaces between the p-type silicon layer 402 and the 25 n-type InP layer 404 with the insulating layer 403 in the optical waveguide portion, the refractive indices of the p-type silicon layer 402 and the n-type InP layer

404 in the optical waveguide portion are modulated. In this structure, an improvement in modulation efficiency is expected to be about two to three times greater, as compared to a case in which Si is used for an n-type layer.

Related Art Literature

Non-Patent Literature

[0006] Non-Patent Literature 1: D. Liang et al., "A Tunable Hybrid III-V-on-Si MOS Microring Resonator with Negligible Tuning Power Consumption", Optical Fiber Communication Conference 2016, Th1K.4, 2016.

Disclosure of Invention

Problem to be Solved by the Invention

[0007] However, the above-described technology has a problem that it is not easy to achieve further improvement in modulation efficiency. To improve modulation efficiency, it is important to increase a carrier-induced refractive index change (carrier plasma effect). In addition, to improve modulation efficiency, it is important to further increase the action (influence) of generated carriers on guided light. In theory, the carrier-induced refractive index change can be further increased by reducing the effective mass of a compound semiconductor and increasing the band filling effect. Furthermore, it is possible that the greater action of the carriers on the guided light is achieved by increasing a light confinement coefficient.

[0008] In fact, however, InP that is used in the conventional technology and forming the InP layer is a stoichiometrically stable composition, and has a uniquely decided crystal structure. Therefore, the material physical properties such as the effective mass and refractive index cannot be adjusted. According to the above-described two factors, it is extremely difficult to improve modulation efficiency.

[0009] The present invention has been made in consideration of the above problems, and has as its object to further improve the modulation efficiency of a charge-accumulation-type optical modulator with a MOS structure.

Means of Solution to the Problem

[0010] According to the present invention, there is provided an optical modulator including a p-type first semiconductor layer made of one of silicon and silicon-germanium formed on a clad layer, an insulating layer formed on the first semiconductor layer, an n-type second semiconductor layer formed from a III-V compound semiconductor made of at least three materials formed on the insulating layer, a first electrode connected to the first semiconductor layer, and a second electrode connected to the second semiconductor layer, wherein part of the first semiconductor layer and part of the second semiconductor layer are arranged so as to overlap each other via the insulating layer in a planar view,

and form an optical waveguide portion where light to be modulated is guided in a direction parallel to a plane of the clad layer, and the light waveguide portion satisfies a single mode condition.

5 [0011] In the optical modulator, the first electrode is formed on a region of the first semiconductor layer where the optical waveguide portion is not being formed.

[0012] In the optical modulator, the second semiconductor layer is formed from stacked multiple
10 compound semiconductor layers, and among the plurality of compound semiconductor layers, the compound semiconductor layer closer to the insulating layer has a smaller band gap energy.

[0013] In the optical modulator, the first
15 semiconductor layer is formed from stacked multiple semiconductor layers, and among the plurality of semiconductor layers, the semiconductor layer closer to the insulating layer has a smaller bandgap energy.

Effect of the Invention

20 [0014] As described above, according to the present invention, since an n-type second semiconductor layer is formed by a III-V compound semiconductor made of three or more materials, it is possible to obtain an excellent effect capable of further improving the modulation
25 efficiency of a charge-accumulation-type optical modulator with a MOS structure.

Brief Description of Drawings

[0015] Fig. 1 is a sectional view showing the arrangement of an optical modulator according to the first embodiment of the present invention;

Fig. 2 is a plan view showing the partial
5 arrangement of the optical modulator according to the first embodiment of the present invention;

Fig. 3 is a sectional view showing the arrangement of an optical modulator according to the second embodiment of the present invention; and

10 Fig. 4 is a sectional view showing the arrangement of a conventional charge-accumulation-type optical modulator with a MOS structure.

Best Mode for Carrying Out the Invention

[0016] Embodiments of the present invention will be
15 described below with reference to the accompanying drawings.

[0017] [First Embodiment]

The first embodiment of the present invention will be described with reference to Figs. 1 and 2. Fig.
20 1 is a sectional view showing the arrangement of an optical modulator according to the first embodiment of the present invention. Fig. 2 is a plan view showing the partial arrangement of the optical modulator according to the first embodiment of the present
25 invention.

[0018] The optical modulator includes a p-type first semiconductor layer 102 formed on a clad layer 101, an

insulating layer 103 formed on the p-type first semiconductor layer 102, and an n-type second semiconductor layer 104 formed on the insulating layer 103. The first semiconductor layer 102 is made of
5 silicon or silicon-germanium. The second semiconductor layer 104 is formed from a compound semiconductor made of three or more materials. The second semiconductor layer 104 is made of, for example, InGaAsP. Furthermore, the optical modulator includes a first
10 electrode 105 connected to the first semiconductor layer 102 and a second electrode 106 connected to the second semiconductor layer 104.

[0019] Part of the first semiconductor layer 102 and part of the second semiconductor layer 104 are arranged
15 so as to overlap each other in a planar view, and forming an optical waveguide portion 121 where light to be modulated is guided in a direction parallel to the plane of the clad layer 101. That is, the insulating layer 103 is sandwiched between the first semiconductor
20 layer 102 and the second semiconductor layer 104 in the stacking direction of the optical waveguide portion 121.

[0020] Note that in the first embodiment, an insulating layer 107 is formed in a region on the clad layer 101 on the formation side of the second electrode
25 106. A side portion of the insulating layer 107 is in contact with a side portion of the first semiconductor layer 102. An insulating layer 108 is formed on the

second semiconductor layer 104. The insulating layers 107 and 108 function as clads, and serve as, together with the clad layer 101, a function of confining light in a region surrounded by the insulating layers in a sectional view.

[0021] The optical waveguide portion 121 extends in the optical waveguide direction indicated by an arrow in the plan view of Fig. 2. Note that Fig. 2 does not illustrate the first electrode 105, the second electrode 106, and the insulating layer 108. In the first embodiment, with respect to the optical waveguide portion 121, the first semiconductor layer 102 extends in one direction, and the second semiconductor layer 104 extends in the other direction. In a region where no insulating layer 103 is formed, that is, the region contained in a region extending from the optical waveguide portion 121 of the first semiconductor layer 102, the first electrode 105 forms an ohmic connection with the surface of the first semiconductor layer 102. The second electrode 106 forms an ohmic connection with the surface of the region extending from the optical waveguide portion 121 of the second semiconductor layer 104. No electrode is arranged in the region of the optical waveguide portion 121 in a planar view. In other words, the first electrode 105 is formed in a region on the first semiconductor layer 102 where the optical waveguide portion 121 is not being formed.

[0022] To form a waveguide mode in the optical waveguide portion 121, the optical waveguide portion 121 satisfies a single mode condition. In the optical waveguide portion 121, majority carriers are accumulated
5 at the interfaces between the first semiconductor layer 102 and the second semiconductor layer 104 with the insulating layer 103. Therefore, the thickness of the first semiconductor layer 102 and that of the second semiconductor layer 104 are appropriately set so that
10 the center of an optical waveguide mode field is arranged in these portions, that is, the interfaces between the first semiconductor layer 102 and the second semiconductor layer 104 with the insulating layer 103.

[0023] A method of manufacturing the optical
15 modulator according to the embodiment will be briefly described below. The first semiconductor layer 102 is, for example, formed on the clad layer 101 by using a well-known SOI substrate, setting a buried insulating layer as the clad layer 101, and patterning a surface
20 silicon layer by a known lithography technique and etching technique.

[0024] Next, the insulating layer 107 is formed adjacent to the first semiconductor layer 102 on the clad layer 101. The insulating layer 107 is made of,
25 for example, silicon oxide, silicon oxynitride, aluminum oxide, or the like. The insulating layer 107 is formed in a planarized state so that its surface is arranged to

be flush with the surface of the first semiconductor layer 102. Next, the insulating layer 103 is formed on the first semiconductor layer 102 and the insulating layer 107. The insulating layer 103 is made of, for example, silicon oxide, silicon oxynitride, aluminum oxide, or the like. Note that an air groove may be formed between the first semiconductor layer 102 and the insulating layer 107.

[0025] On the other hand, an InGaAsP layer with a predetermined composition ratio is epitaxially grown on a growth substrate made of InP by well-known metal-organic chemical vapor deposition. The grown InGaAsP layer is bonded onto the above-described insulating layer 103. After that, the growth substrate is removed. Then, the second semiconductor layer 104 is formed by patterning the InGaAsP layer formed on the insulating layer 103 by the known lithography technique and etching technique.

[0026] Next, the surface of the first semiconductor layer 102 is exposed by forming an opening in the insulating layer 103 at a location where the first electrode 105 is formed, and the first electrode 105 is formed there. The first electrode 105 is made of, for example, Ti. The second electrode 106 is formed on the second semiconductor layer 104. The second electrode 106 is made of, for example, AuGeNi. Each electrode is formed by, for example, a well-known lift-off method.

Furthermore, the insulating layer 108 is formed on the second semiconductor layer 104 and the insulating layer 103. Note that the insulating layer 108 need not always be formed, and an air layer may be used instead.

5 However, by forming the insulating layer 108, the second semiconductor layer 104 can be protected from the surrounding environment.

[0027] According to the first embodiment, since the second semiconductor layer 104 is formed by a compound semiconductor made of three or more materials, it is possible to improve the modulation efficiency of the optical modulator, as will be described below.

[0028] The effective mass and refractive index of a ternary or quaternary compound semiconductor can be controlled by controlling a composition. It is possible to improve light confinement and a carrier-induced refractive index change.

[0029] For example, the relationship between a composition y and a band gap energy E_g of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ is given by:

$$E_g = 1.344 - 0.738y + 0.138y^2$$

[0030] As is well known, a refractive index change induced by current injection in a semiconductor has the carrier plasma effect, band filling effect, and band gap reduction effect. In consideration of these effects, when an electron concentration is changed by $2 \times 10^{18} \text{ cm}^{-3}$, the refractive index of InP changes by 0.0094.

Conversely, when the electron concentration is changed by $2 \times 10^{18} \text{ cm}^3$, the refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.95 \text{ eV}$ changes by 0.013, the refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.92 \text{ eV}$ changes by 0.0145, and the refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.89 \text{ eV}$ changes by 0.016.

[0031] Note that $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.95 \text{ eV}$ has a band gap wavelength λ of $1.3 \text{ }\mu\text{m}$, $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.92 \text{ eV}$ has a band gap wavelength λ of $1.35 \text{ }\mu\text{m}$, and $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with $E_g = 0.89 \text{ eV}$ has a band gap wavelength λ of $1.4 \text{ }\mu\text{m}$.

[0032] As for $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$, as the band gap energy decreases by changing the composition ratio, a carrier-induced refractive index change increases to be greater than that of InP of a binary material.

[0033] In general, as for $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$, as the band gap energy decreases, the refractive index increases. The light confinement effect in the optical waveguide portion 121 increases by using a material with a high refractive index for the second semiconductor layer 104 forming the optical waveguide portion 121, thereby making it possible to strengthen the light intensity (distribution) in the optical waveguide portion 121. As a result, majority carriers generated at the interface of the second semiconductor layer 104 with the insulating layer 103 in the optical waveguide portion 121 can be made to more strongly work on light that is

guided to the optical waveguide portion 121. Therefore,
a multicomponent compound semiconductor forming the
second semiconductor layer 104 desirably has a
composition with a smaller band gap energy.

5 [0034] As described above, by forming the second
semiconductor layer 104 from a semiconductor with a
smaller band gap energy, it is possible to firstly
increase a refractive index change by a carrier
concentration change, and secondly increase the
10 influence of the generated carriers on the guided light.
Note that to prevent inter-band absorption in the second
semiconductor layer 104, the band gap energy needs to be
equal to or greater than an energy corresponding to the
wavelength of the light to be modulated. For example,
15 when the wavelength of the light to be modulated is 1.55
 μm , the band gap energy of the second semiconductor
layer 104 needs to be 0.8 eV or greater.

[0035] The first semiconductor layer 102 is not
always made of silicon, and may be made of a silicon-
20 germanium mixed crystal material with a smaller
effective mass. Furthermore, the insulating layer 103
is thinned to implement a desired capacity of the CR
time constant within a range in which dielectric
breakdown resistance and tunnel current prevention
25 performance are obtained.

[0036] [Second Embodiment]

The second embodiment of the present invention

will be described with reference to Fig. 3. Fig. 3 is a sectional view showing the arrangement of an optical modulator according to the second embodiment of the present invention.

5 [0037] The optical modulator includes a p-type first semiconductor layer 102 formed on a clad layer 101, an insulating layer 103 formed on the first semiconductor layer 102, and an n-type second semiconductor layer 204 formed on the insulating layer 103. Furthermore, the
10 optical modulator includes a first electrode 105 connected to the first semiconductor layer 102, and a second electrode 106 connected to the second semiconductor layer 204.

[0038] Part of the first semiconductor layer 102 and
15 part of the second semiconductor layer 104 are arranged so as to overlap each other in a planar view, and form an optical waveguide portion 121 where light to be modulated is guided in a direction parallel to the plane of the clad layer 101. That is, the insulating layer
20 103 is sandwiched between the first semiconductor layer 102 and the second semiconductor layer 104 in the stacking direction of the optical waveguide portion 121.

[0039] In the second embodiment, the second semiconductor layer 204 is formed from a plurality of
25 stacked compound semiconductor layers 204a and 204b. The band gap energies of the compound semiconductor layers 204a and 204b are different from each other, and

the compound semiconductor layer 204a closer to the insulating layer 103 has a smaller band gap energy. The arrangement other than the second semiconductor layer 204 is the same as in the above-described first embodiment. In the second embodiment as well, the insulating layer 107 is formed adjacent to the first semiconductor layer 102 on the clad layer 101, and the insulating layer 108 is formed on the second semiconductor layer 204.

10 [0040] A region where a refractive index changes by carriers generated at the interfaces of the first semiconductor layer 102 and the second semiconductor layer 204 with the insulating layer 103 in the optical waveguide portion 121 is close to the interfaces of the first semiconductor layer 102 and the second semiconductor layer 204 with the insulating layer 103, at which carriers are accumulated. Therefore, the layer having greater refractive index change and having smaller band gap energy is arranged near the insulating layer 103. As described above, the compound semiconductor layer 204a with the smaller band gap energy is arranged on the side of the insulating layer 103.

25 [0041] This arrangement is characteristic in that the relation between the refractive indices is described as, "compound semiconductor layer 204a > compound semiconductor layer 204b". With this arrangement, a

difference in refractive index is generated in the stacking direction in the second semiconductor layer 204. Thus, the light guided in the optical waveguide portion 121 concentrates on the side of the compound semiconductor layer 204a with the higher refractive index, and light is more strongly confined near the interface with the insulating layer 103, at which the carriers are accumulated. As a result, the action of the carriers on the guided light can be increased.

10 [0042] Note that in the second embodiment as well, the thicknesses of the first semiconductor layer 102 and compound semiconductor layers 204a and 204b are set appropriately so that the center of the optical waveguide mode field is arranged in the portion in the optical waveguide portion 121 where majority carriers are accumulated, that is, near the interface of the first semiconductor layer 102 or the second semiconductor layer 204 with the insulating layer 103. Furthermore, in the second embodiment as well, the first electrode 105 is formed in a region except for the optical waveguide portion 121 on the first semiconductor layer 102, and no electrode is arranged in a region of the optical waveguide portion 121 in a planar view.

25 [0043] As for a compound semiconductor having a smaller band gap, a carrier-induced refractive index change is greater while absorption by the carriers is also greater. Therefore, it is possible to reduce an

absorption loss of the guided light by forming the compound semiconductor layer 204b having a smaller loss, in a region not including the periphery of the interface, where carrier accumulation does not occur.

5 [0044] In the second embodiment, the first semiconductor layer 102 is made of silicon or silicon-germanium, the second semiconductor layer 204 has the stacked structure of the compound semiconductor layers 204a and 204b with different band gap energies, and the
10 compound semiconductor layer closer to the insulating layer 103 has the smaller band gap energy. However, similarly to the second semiconductor layer 204, the first semiconductor layer 102 may also have the stacked structure of semiconductor layers with different band
15 gap energies, and may be configured so that the semiconductor layer closer to the insulating layer has a smaller band gap energy. In the first embodiment as well, the first semiconductor layer 102 may have the above-described stacked structure. The band gap and
20 refractive index of the first semiconductor layer 102 can be controlled by a composition of a silicon-germanium mixed crystal material, and it may be possible to obtain the same effect as that described above in the first semiconductor layer.

25 [0045] As described above, according to the present invention, since the n-type second semiconductor layer is formed by the III-V compound semiconductor made of

three or more materials, it is possible to further improve the modulation efficiency of the charge-accumulation-type optical modulator with the MOS structure.

5 [0046] Note that the present invention is not limited to the above-described embodiments, and it is obvious that various modifications and combinations can be made within the technical scope of the present invention by those skilled in the art in this field. For example,
10 InGaAsP has been exemplified above. However, the present invention is not limited to this, and the second semiconductor layer may be formed from another ternary or quaternary III-V compound semiconductor. They need not always be crystal.

15 Explanation of the Reference Numerals and Signs

[0047] 101...clad layer, 102...first semiconductor layer, 103...insulating layer, 104...second semiconductor layer, 105...first electrode, 106...second electrode, 107...insulating layer, 108...insulating
20 layer

C L A I M S

1. An optical modulator comprising:
 - a p-type first semiconductor layer made of one of silicon and silicon-germanium formed on a clad layer;
 - an insulating layer formed on the first semiconductor layer;
 - an n-type second semiconductor layer formed from a III-V compound semiconductor made of at least three materials formed on the insulating layer;
 - a first electrode connected to the first semiconductor layer; and
 - a second electrode connected to the second semiconductor layer,wherein part of the first semiconductor layer and part of the second semiconductor layer are arranged so as to overlap each other via the insulating layer in a planar view, and form an optical waveguide portion where light to be modulated is guided in a direction parallel to a plane of the clad layer, and
the light waveguide portion satisfies a single mode condition.
2. The optical modulator according to claim 1, wherein the first electrode is formed on a region of the first semiconductor layer where the optical waveguide portion is not being formed.

3. The optical modulator according to claim 1 or 2, wherein the second semiconductor layer is formed from a plurality of stacked compound semiconductor layers, and among the plurality of compound semiconductor layers, the compound semiconductor layer closer to the insulating layer has a smaller band gap energy.

4. The optical modulator according to any one of claims 1 to 3, wherein the first semiconductor layer is formed from a plurality of stacked semiconductor layers, and among the plurality of semiconductor layers, the semiconductor layer closer to the insulating layer has a smaller bandgap energy.