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(54) **OPTOELECTRONIC DEVICE**

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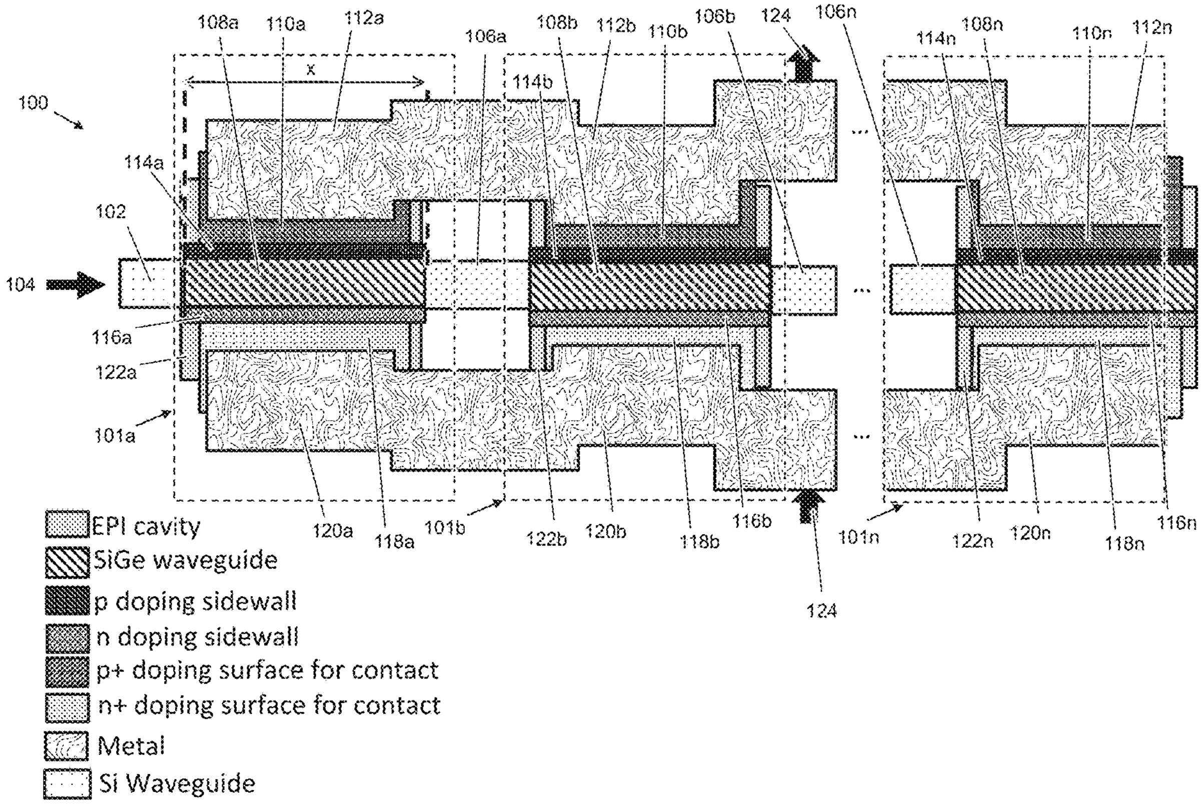
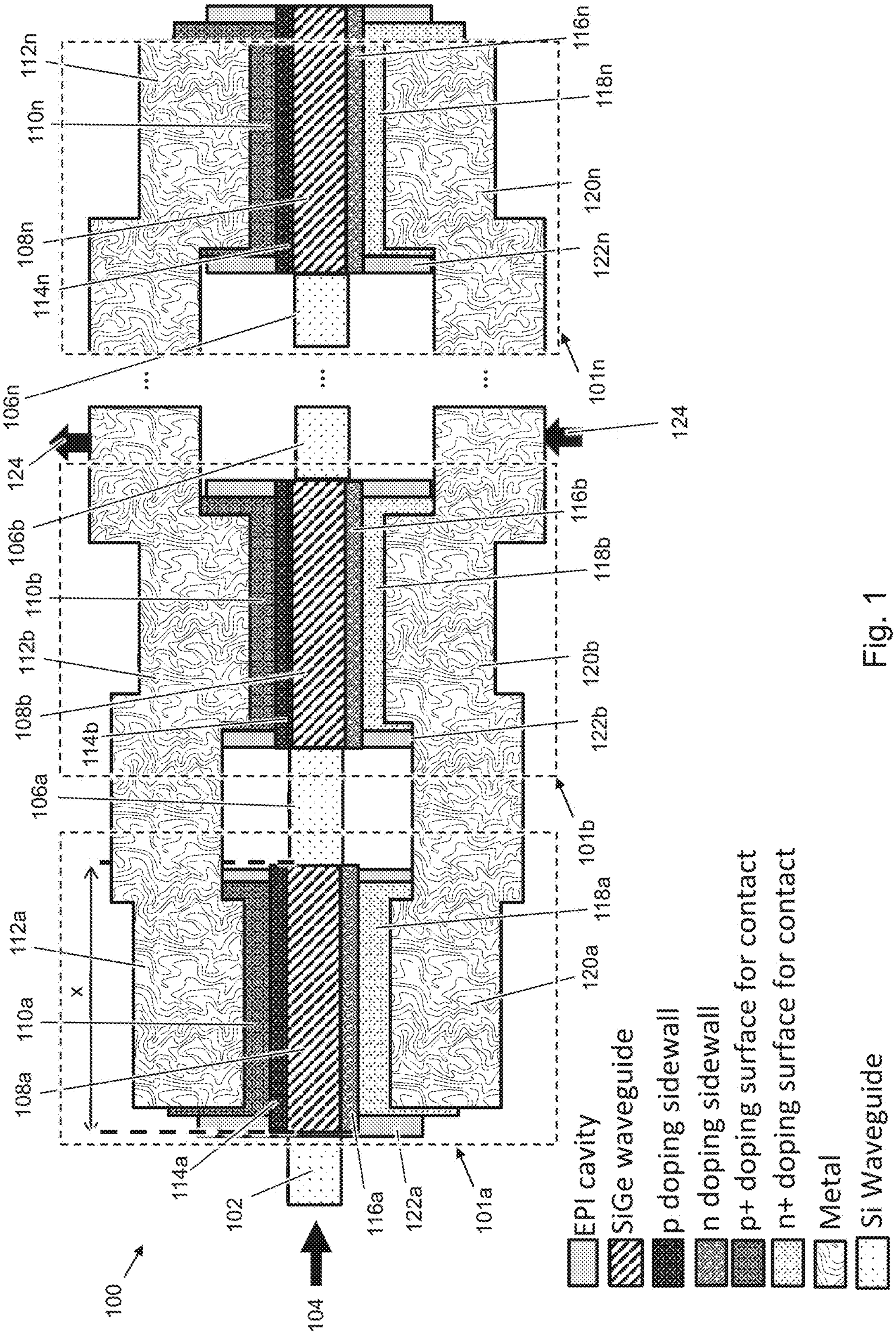
(57) **ABSTRACT**

An optoelectronic device. The device comprising: an input waveguide, which receives an optical signal; a multistage photodiode detector, comprising a plurality of photodiode elements connected in series, one of the photodiode elements of the plurality of photodiode elements being connected to the input waveguide and configured to receive the optical signal therefrom; and a first electrode and a second electrode, wherein the first electrode is connected to a first contact of each of the plurality of photodiode elements, and the second electrode is connected to a second contact of each of the plurality of photodiode elements.




100
104
102
101a
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108b
112b
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118b
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124
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106n
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122n
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120n
110n
118n
112n
116n
...
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EPI cavity
SiGe waveguide
p doping sidewall
n doping sidewall
p+ doping surface for contact
n+ doping surface for contact
Metal
Si Waveguide

Fig. 1

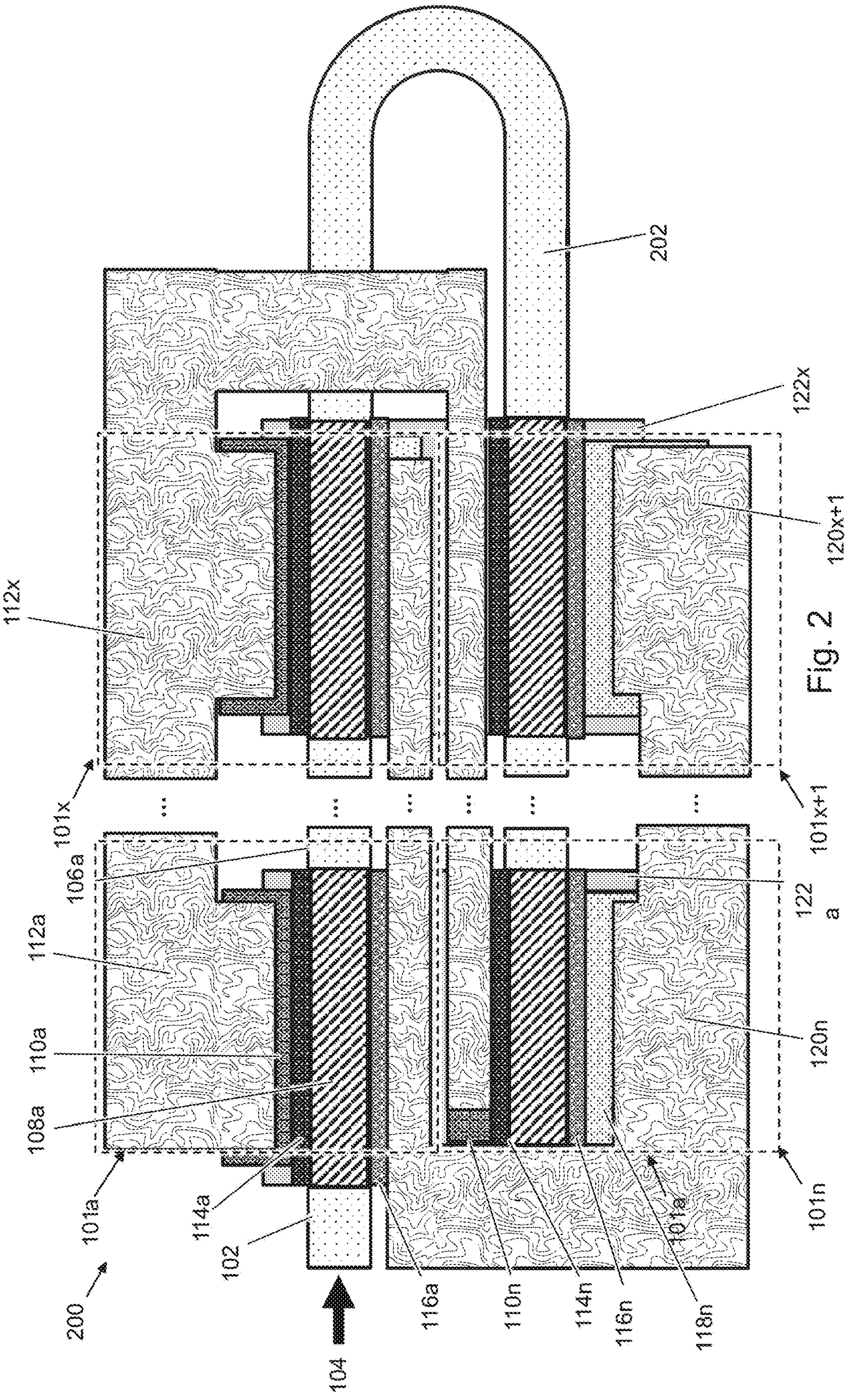
200
104
102
101a
108a
110a
112a
106a
101x
112x
114a
116a
110n
114n
116n
118n
101a
101n
120n
122
a
101x+1
120x+1
122x
202
...

Fig. 2

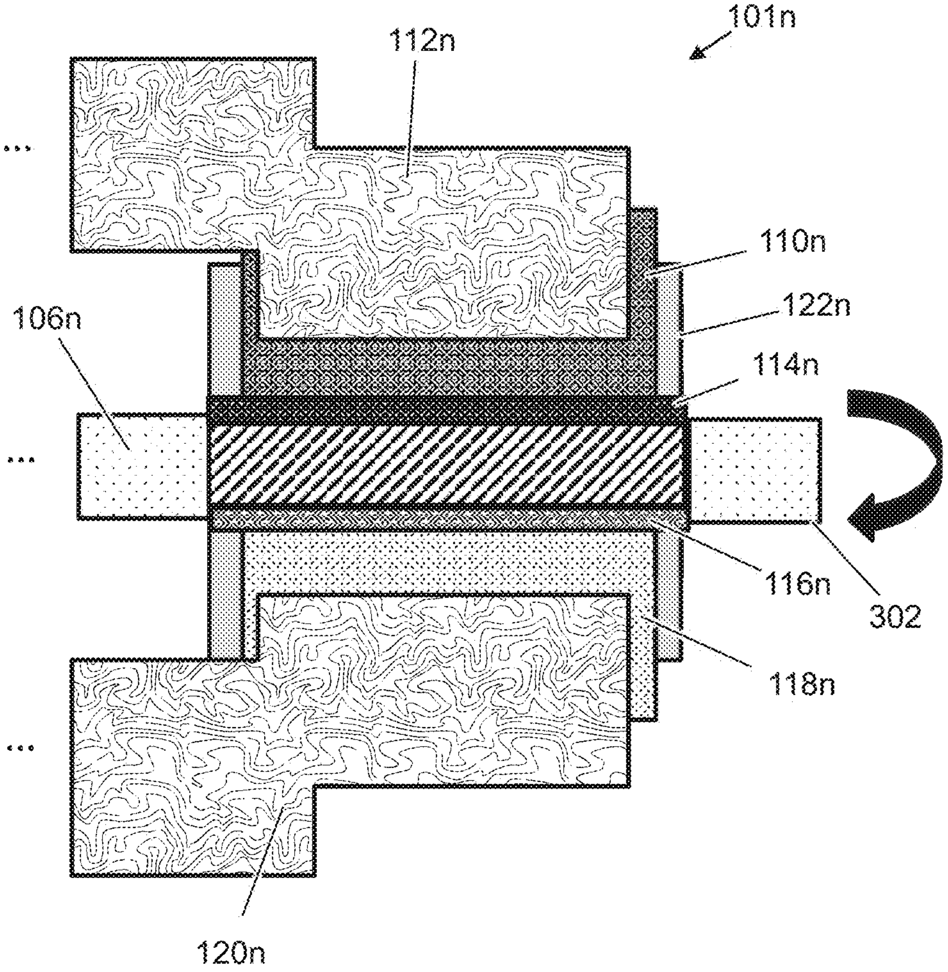

Fig. 3

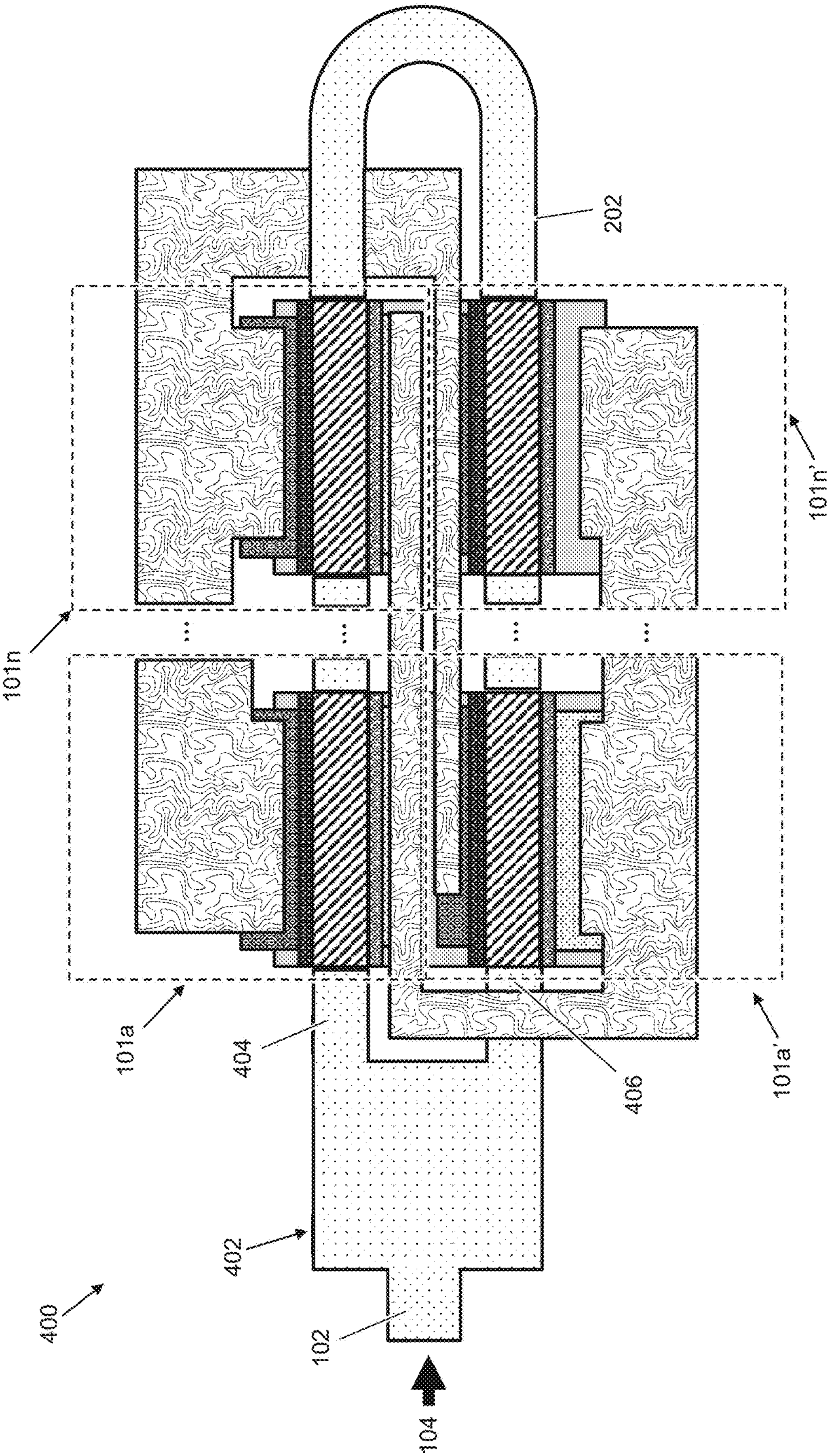

Fig. 4

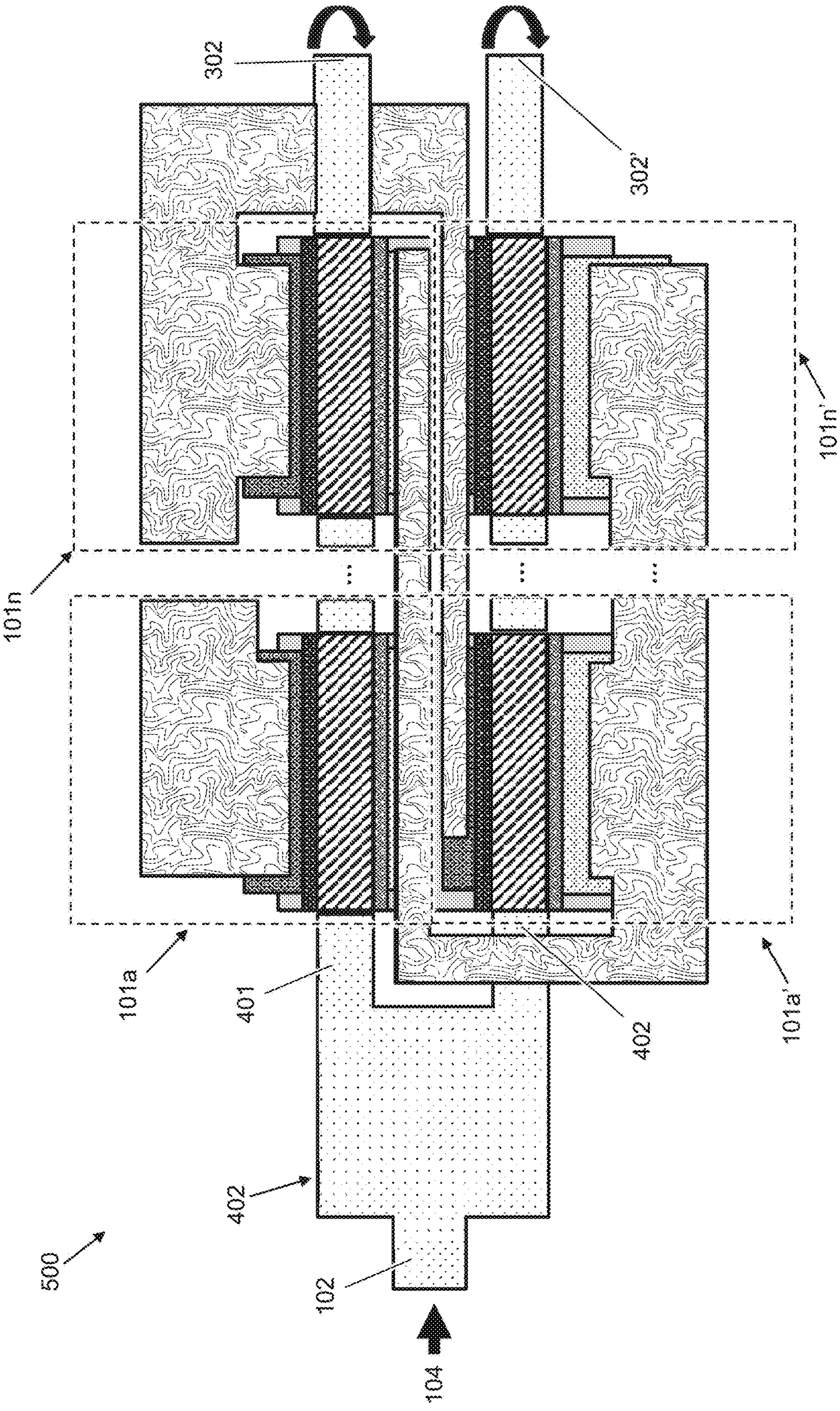

Fig. 5

OPTOELECTRONIC DEVICE

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims priority to United Kingdom Patent Application No. 2116568.3, filed in the United Kingdom Intellectual Property Office on Nov. 17, 2021, entitled “OPTOELECTRONIC DEVICE”, which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to an optoelectronic device.

BACKGROUND

[0003] In order to simplify and reduce the cost of manufacturing optoelectronic devices, it is desirable to have several active components (e.g. an electro-absorption modulator, laser, and a corresponding power monitor photodiode detector) made out of the same material or at least the same material system.

[0004] Typically, however, using the same materials would result in either an inefficient modulator, inefficient laser, or an inefficient photodiode as the materials can only be optimised for one of the components. This is because high speed (e.g. 10 s or GHz) EAM modulators need to be small and short in optical length. The performance of an EAM is defined in relation to how much of the light is modulated. The generated photocurrent is only a secondary consideration.

[0005] Whereas photodiodes should be as efficient as possible in converting light into photocurrent. Speed is not important for photodiodes (kHz to MHz is more than sufficient for most uses) and so they can be longer in optical length.

[0006] A further consideration is that EAM modulators typically operate at a wavelength near, but slightly longer than, the bandgap, as minimising the transmission loss under modulation is a key consideration. Whereas, photodiodes typically operate at wavelengths shorter than the bandgap in order to maximise the absorption efficiency and conversion to photocurrent.

[0007] Therefore photodiodes operating at a wavelength optimized for an EAM modulator will have a degraded absorption efficiency, and moreover the total absorption will depend on wavelength, temperature, and bias voltage. This type of photodiode can be successful, if it is made long enough so that the light signal is converted to photocurrent with a net efficiency which is independent of wavelength, temperature, and bias voltage.

[0008] However implementation of long photodiodes is difficult, particularly in implementations of silicon based photonic integrated circuits with integrated silicon germanium epitaxially grown active waveguides. This type of integration generally has a size limitation on the silicon germanium elements.

SUMMARY

[0009] Accordingly, in a first aspect, embodiments of the present invention provide an optoelectronic device comprising:

[0010] an input waveguide, which is configured to receive an optical signal;

[0011] a multistage photodiode detector, comprising a plurality of photodiode elements connected in series, one of the photodiode elements of the plurality of photodiode elements being connected to the input waveguide and configured to receive the optical signal therefrom; and

[0012] a first electrode and a second electrode, wherein the first electrode is connected to a first contact of each of the plurality of photodiode elements, and the second electrode is connected to a second contact of each of the plurality of photodiode elements.

[0013] Accordingly, such a multistage photodiode detector can be formed from the same material or material system as other components of a photonic integrated circuit in which the multistage photodiode detector may be integrated.

[0014] The optoelectronic device may have any one or, to the extent that they are compatible, any combination of the following optional features.

[0015] Each photodiode element may comprise a p-i-n junction extending across a waveguide. The first contact of each of the plurality of photodiode elements may be an n+ doped region, and the second contact of each of the plurality of photodiode elements may be a p+ doped region. Alternatively, each photodiode element may comprise a p-n junction extending across a waveguide. Again, the first contact of each of the plurality of photodiode elements may be an n+ doped region, and the second contact of each of the plurality of photodiode elements may be a p+ doped region. The plurality of photodiode elements may comprise a mixture of p-n and p-i-n junctions.

[0016] Each photodiode element may be located within a cavity of a silicon-on-insulator wafer. Each photodiode element may be an epitaxially formed photodiode element, i.e. one formed of an epitaxial crystalline structure. By cavity, it may be meant a region of the silicon-on-insulator wafer which has been previously removed (and may be subsequently filled, e.g. with a different material via epitaxy).

[0017] The optoelectronic device may comprise a plurality of passive waveguides, each of which may connect a pair of the plurality of photodiode elements. Each passive waveguide may be formed from silicon. For example, each passive waveguide may be a silicon waveguide within a silicon device layer (or silicon-on-insulator layer) of a silicon-on-insulator wafer.

[0018] A final photodiode element of the plurality of photodiode elements may be connected at a terminating end to a high reflectivity mirror. Accordingly, the total number of photodiode elements may be reduced, as the optical signal can pass through the same photodiode element multiple times. By terminating end, it may be meant an end of the waveguide of the photodiode element which does not then go on to connect to a further photodiode element.

[0019] A passive waveguide, located between a pair of the plurality of photodiode elements, may have a U-shape. By ‘U-shaped’ it may be meant that the passive waveguide comprises a first straight section, a curved connecting section, and a second straight section, where the curved connection section includes a 180° curve. Accordingly, the total footprint of the multistage photodiode detector can be reduced, as the length can be reduced. The first electrode and the second electrode may each have a U-shape. The legs of the first and second electrode may lie adjacent to one another, with the ‘bars’ of each U-shaped electrode being distal to one another. The two U-shaped electrodes may partially overlap, in that a leg of one is positioned between the legs of the other. Pairs of the plurality of photodiode elements which are spatially adjacent may be located within a same cavity of a silicon-on-insulator wafer. By spatially adjacent, it may be meant those photodiode elements which are adjacent in a direction transversal to the guiding direction of the photodiode elements. The adjacent photodiode elements may be those which are not directly optically coupled, save for a pair which are directly coupled via the U-shaped passive waveguide.

[0020] The input waveguide may be connected to a splitter, a first output of the splitter may be connected to a first photodiode element and a second output of the splitter may be connected to a second photodiode element.

[0021] The first photodiode element may be part of a first sub-group of the plurality of photodiode elements and the second photodiode element may be part of a second sub-group of the plurality of photodiode elements, and a final photodiode element of the first sub-group may be connected to a final photodiode element of the second sub-group via a U-shaped passive waveguide.

[0022] The first photodiode element may be part of a first sub-group of the plurality of photodiode elements and the second photodiode element may be part of a second sub-group of the plurality of photodiode elements, and a final photodiode element of the first sub-group may be connected at a terminating end to a first high reflectivity mirror and a final photodiode element in the second sub-group may be connected at a terminating end to a second high reflectivity mirror.

[0023] The input waveguide may be formed from silicon, and the photodiode elements may be formed from silicon germanium. The photodiode elements may each comprise an active waveguide, which is formed from silicon germanium.

[0024] The optoelectronic device may be a power monitor. The optoelectronic device may be a power monitor for an electro-absorption modulator. The optoelectronic device may be a power monitor for a laser. The optoelectronic device may be connected to the laser after the laser and before an electro-absorption modulator. The optoelectronic device may be connected to a low percentage tap.

[0025] In a second aspect, embodiments of the invention provide an array comprising a plurality of the power monitors of the first aspect, wherein each power monitor is connected to a respective laser or electro-absorption modulator.

[0026] In a third aspect, embodiments of the invention provide a method of monitoring a power output of a laser or an electro-absorption modulator, using the power monitor of the first aspect, the method comprising the steps of:

[0027] providing a signal from the laser or electro-absorption modulator to the input waveguide; and

[0028] detecting, using the multistage photodiode detector, a power level of the signal.

[0029] The signal may be received from a low percentage tap. By low percentage tap, it may be meant a tap coupler which couples a relatively low percentage (e.g. less than 10%, less than 5%, or less than 1%) of a signal output from the laser or electro-absorption modulator into the input waveguide of the power monitor.

[0030] In a fourth aspect, embodiments of the invention provide a photonic integrated circuit for use as a transmission device, the photonic integrated circuit comprising the array of the second aspect.

[0031] Further aspects of the present invention provide: a computer program comprising code which, when run on a computer, causes the computer to perform the method of the third aspect; a computer readable medium storing a computer program comprising code which, when run on a computer, causes the computer to perform the method of the third aspect; and a computer system programmed to perform the method of the third aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

[0032] Embodiments of the invention will now be described by way of example with reference to the accompanying drawings in which:

[0033] FIG. **1** is a top view of an optoelectronic device;

[0034] FIG. **2** is a top view of a variant optoelectronic device;

[0035] FIG. **3** is a top view of an end photodiode element;

[0036] FIG. **4** is a top view of a variant optoelectronic device; and

[0037] FIG. **5** is a top view of a variant optoelectronic device.

DETAILED DESCRIPTION AND FURTHER OPTIONAL FEATURES

[0038] Aspects and embodiments of the present invention will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art. All documents mentioned in this text are incorporated herein by reference

[0039] FIG. **1** is a top view of an optoelectronic device **100**. The device comprises an input waveguide **102**, which receives an optical signal **104**. This optical signal can be, for example, from a tap on a laser output or a modulator, so as to monitor the power output of the laser or modulator.

[0040] The device **100** also includes a plurality of photodiode elements **101***a*, **101***b*, etc. to **101***n*, which combined form a multistage photodiode detector. The first photodiode element **101***a* is connected to the input waveguide at a first end, and to a passive waveguide **106***a* at a second end. The passive waveguide connects photodiode element **101***a* to the adjacent photodiode element **101***b*. Similarly, passive waveguide **106***b* connects photodiode element **101***b* to the next photodiode element, and so on.

[0041] A first electrode connects to a first contact of each of the photodiode elements. For example, a first contact **120***a* of the electrode connects to a portion of the first photodiode element **101***a*. Similarly, a second contact **120***b* of the electrode connects to a same portion of the second photodiode element **101***b*. A second electrode connects to a first contact of each of the photodiode elements. For example, a first contact **112***a* of the electrode connects to a portion of the first photodiode element **101***a*. Similarly, a second contact **112***b* of the electrode connects to a same portion of the second photodiode element **101***b*.

[0042] Each photodiode element comprises a cavity **122***a*, etched into a silicon-on-insulator wafer. The input waveguide **102** and passive waveguides **106***a*-**106***n* are silicon waveguides formed in the silicon-on-insulator (or silicon device layer) of the silicon-on-insulator wafer, and are themselves formed from silicon. The depth of each cavity **122***a* is such that an active waveguide **108***a*-**108***n* of each photodiode element is aligned with the adjacent passive waveguides.

[0043] The active waveguides **108***a*-**108***n* are formed from silicon germanium (SiGe), and comprise a ridge or rib region in the centre and a slab region on either lateral side of the ridge or rib (lateral being a direction typically perpendicular to the guiding direction of the waveguide). Each ridge or rib includes an n doped sidewall **116***a-n* and a p doped sidewall **114***a-n*. A centre portion of each ridge or rib is undoped or only unintentionally doped, and so the ridge or rib forms a P-I-N junction and thereby operates as a photodiode when connected to electrodes. In an alternative embodiment, not shown, the ridge or rib is entirely doped and so forms a P-N junction.

[0044] The p doped sidewall **114***a-n* is connected to a p+ doped region **110***a-n* of the respective slab. By p+, it is meant that the region of the slab is doped to a dopant concentration level higher than the respective p doped sidewall **114***a-n*. Similarly, then doped sidewall **116***a-n* is connected to an n+ doped region **118***a-n* of the respective slab. By n+, it is meant that the region of the slab is doped to a dopant concentration level higher than the n doped sidewall **116***a-n*. The electrode contacts **120***a-n* and **112***a-n* connect to the p+ and n+ doped regions of the respective slab. The increased dopant concentration in the p+ and n+ doped regions reduces series resistance in the connections to the electrodes.

[0045] In use, the optical signal **104** is passed from the input waveguide **102** to the first photodiode element **101***a*. The P-I-N or P-N junction in the photodiode element **101***a* then partially converts the optical signal to an electrical current **124**, which is read from the photodiode element. The partially converted optical signal then passes along the passive waveguide **106***a* to the second photodiode element **101***b*, which also partially converts the optical signal, and so on.

[0046] A last photodiode element **101***n* terminates with the end of the active waveguide **106***n*, and so the number of photodiode elements should be chosen so as to ensure optimum power monitoring. n may take a value of between 2 and 5, typically fewer elements will be used if a mirror is provided at the end of the optoelectronic device (as discussed below).

[0047] As a result, despite the photodiode elements having not been individually optimised, an accurate power reading can be taken from the optoelectronic device to which the photodiode elements are connected. Moreover, this can be achieved given the restraints discussed above relating to the choice of material system, and also the maximum length 'x' of the cavities **122***a*.

[0048] FIG. **2** is a top view of a variant optoelectronic device **200**. Where the device **200** shares features with the device **100**, like features are indicated by like reference numerals. As before, the device comprises a plurality of photodiode elements **101***a*-**101***n*. However, in contrast to the device **100**, one of the passive waveguides **202** between a pair (**101***x* and **101***x*+**1**) of photodiode elements has a U-shape. Therefore light passing through the multistage photodiode detector initially travels in a first direction (from the input waveguide **102** in the direction indicated by arrow **104**) before passing through an approximately 180° turn, and so traveling in a second direction antiparallel to the first.

[0049] Moreover, each cavity **122** in device **200** is wider than the cavities in device **100**. This is because a pair of photodiode elements (e.g. **101***a* and **101***n* or **101***x* and **101***x*+1) reside in each. In an alternative example, the cavities **122** in device **200** are the same width as the cavities in device **100** e.g. because the cavities in device **100** are oversized.

[0050] These differences allows the overall footprint of the multistage photodiode detector to be reduced. Moreover, each of the first **112** and second 120 electrodes can have a U-shape (one rotated 180° relative to the other). The U-shaped electrodes overlap in that a 'leg' (i.e. the elongate members extending parallel to the active waveguides **108***a*-**108***n*) from each of the U-shaped electrodes are adjacent to one another, so as to further reduce the footprint of the multistage photodiode detector. Said another way, the footprint of the U-shaped electrodes overlaps in that the 'leg' of one U-shaped electrode sits within the bend of U of another.

[0051] FIG. **3** is a top view of a variant end photodiode element **101***n*. Where it shares features with the photodiode elements discussed previously, like features are indicated by like reference numerals. In contrast to the end photodiode elements shown in FIGS. **1** and **2**, the photodiode element **101***n* in FIG. **3** terminates in high reflectivity mirror **302**. This could be, for example, a facet (e.g. etched facet) with HR (high reflectivity) coating or a Sagnac reflector (also known as a Sagnac loop reflector, Sagnac mirror, or Sagnac loop mirror). This high reflectivity mirror causes the signal passing through the multistage photodiode detector to perform a double pass through the detector and so the overall number of elements can be reduced (as each is used twice).

[0052] FIG. **4** is a top view of a variant optoelectronic device **400**. Where the device **400** shares features with the devices **100** and **200** shown previously, like features are indicated by like reference numerals. The device **400** differs from those shown previously in that input waveguide **102** does not connect directly to any photodiode element of the multistage photodiode detector. Instead, the input waveguide **102** connects to a splitter **402**, for example a multimode interference splitter (MMI) which divides the signal and provides outputs at a first output **404** and a second output **406**.

[0053] The first output **404** is connected to a first photodiode element **101***a* of a first sub-group of the plurality of photodiodes. The second output **406** is connected to a first photodiode element **101***a*' of a second sup-group of the plurality of photodiodes. In this way, light is provided to both the first and second sub-groups of the plurality of photodiodes. Thereafter each sub-group can be considered its own multistage photodiode detector.

[0054] In the example shown in FIG. **4**, the end photodiode elements **101***n* and **101***n*' of each sub-group are connected via a U-shaped waveguide **202**. Therefore any residual optical signal, which has not yet been converted to photocurrent in the preceding sub-group of photodiode elements, will then travel back towards the input waveguide and so pass through the other sub-group of photodiode elements and so be converted to photocurrent.

[0055] FIG. **5** is a top view of a variant optoelectronic device **500**. Where the device **500** shares features with the devices **100**, **200**, and **400** shown previously, like features are indicated by like reference numerals. The device **500** in FIG. **5** differs from the device **400** in FIG. **4** in that the end photodiode elements **101***n* and **101***n*' of each sub-group do not connect to each other via a U-shaped waveguide. Instead, each terminates in a high reflectivity mirror **302** and **302'** in the same manner as the end photodiode element shown in FIG. **3**. Therefore after passing through all of the photodiode elements in a given sub-group, any residual optical signal is reflected back through the same sub-group towards the input waveguide.

[0056] The devices **100**, **200**, **400**, and **500**, can be disposed in an array, each connected to a respective tap on a laser output or electro-absorption modulator and so the power of different signals (e.g. different wavelengths, or on different channels) can be monitored.

[0057] While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

LIST OF FEATURES

[0058] **100** Optoelectronic device
[0059] **101***n* Photodiode element
[0060] **102** Input waveguide
[0061] **104** Optical signal
[0062] **106***n* Passive waveguide
[0063] **108***n* Active waveguide
[0064] **110***n* p+ doped region
[0065] **112***n* Contact
[0066] **114***n* p doped region of active waveguide
[0067] **116***n* n doped region of active waveguide
[0068] **118***n* n+ doped region
[0069] **120***n* Contact
[0070] **122***n* Cavity
[0071] **124** Photocurrent
[0072] **202** U-shaped passive waveguide
[0073] **302** High reflectivity mirror
[0074] **400** Splitter
[0075] **401** First splitter output
[0076] **402** Second splitter output

1. An optoelectronic device comprising:

an input waveguide, which is configured to receive an optical signal;

a multistage photodiode detector, comprising a plurality of photodiode elements connected in series, one of the photodiode elements of the plurality of photodiode elements being connected to the input waveguide and configured to receive the optical signal therefrom; and

a first electrode and a second electrode, wherein the first electrode is connected to a first contact of each of the plurality of photodiode elements, and the second electrode is connected to a second contact of each of the plurality of photodiode elements.

2. The optoelectronic device of claim **1**, wherein each photodiode element comprises a p-i-n junction extending across a waveguide.

3. The optoelectronic device of claim **1**, wherein each photodiode element is located within a cavity of a silicon-on-insulator wafer.

4. The optoelectronic device of claim **1**, further comprising a plurality of passive waveguides, each of which connects a pair of the plurality of photodiode elements.

5. The optoelectronic device of claim **1**, wherein a final photodiode element of the plurality of photodiode elements is connected at a terminating end to a high reflectivity mirror.

6. The optoelectronic device of claim **1**, wherein a passive waveguide, located between a pair of the plurality of photodiode elements, has a U-shape.

7. The optoelectronic device of claim **6**, wherein the first electrode and second electrode each have a U-shape.

8. The optoelectronic device of claim **6**, wherein pairs of the plurality of photodiode elements which are spatially adjacent are located within a same cavity of a silicon-on-insulator wafer.

9. The optoelectronic device of claim **1**, wherein the input waveguide is connected to a splitter, a first output of the splitter being connected to a first photodiode element and a second output of the splitter being connected to a second photodiode element.

10. The optoelectronic device of claim **9**, wherein the first photodiode element is part of a first sub-group of the plurality of photodiode elements and the second photodiode element is part of a second sub-group of the plurality of photodiode elements, and wherein a final photodiode element in the first sub-group is connected to a final photodiode element in the second sub-group via a U-shaped passive waveguide.

11. The optoelectronic device of claim **9**, wherein the first photodiode element is part of a first sub-group of the plurality of photodiode elements and the second photodiode element is part of a second sub-group of the plurality of photodiode elements, and wherein a final photodiode element in the first sub-group connected at a terminating end to a first high reflectivity mirror and a final photodiode element in the second sub-group is connected at a terminating end to a second high reflectivity mirror.

12. The optoelectronic device of claim **1**, wherein the input waveguide is formed from silicon, and the photodiode elements are formed from silicon germanium.

13. The optoelectronic device of claim **1**, wherein the optoelectronic device is a power monitor.

14. An array comprising a plurality of the power monitors according to claim **13**, each power monitor being connected to a respective laser or electro-absorption modulator.

15. A method of monitoring a power output of an electro-absorption modulator, using the power monitor of claim **13**, comprising the steps of:

providing a signal from a laser or an electro-absorption modulator to the input waveguide; and

detecting, using the multistage photodiode detector, a power level of the signal.

16. A photonic integrated circuit, for use as a transmission device, comprising the array of claim **14**.

* * * * *