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Luo et al.

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(54) **PHOTODETECTOR ARRANGEMENT**

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H01L 27/144	(2006.01)
H01L 31/028	(2006.01)
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G02B 6/28	(2006.01)

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USPC 257/432
See application file for complete search history.

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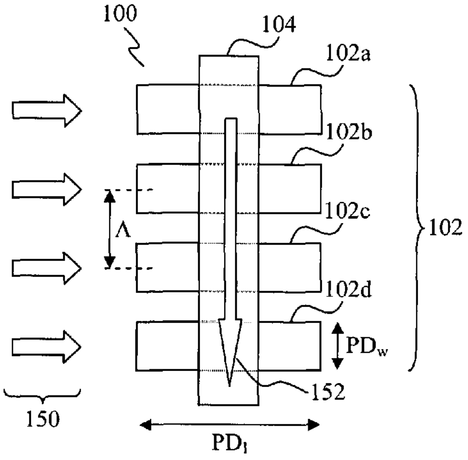
(57) **ABSTRACT**

According to embodiments of the present invention, a photodetector arrangement is provided. The photodetector arrangement includes a plurality of germanium-based photodetectors, each germanium-based photodetector configured to receive an optical signal and to generate an electrical signal in response to the received optical signal, and an electrode arrangement arranged to conduct the electrical signals.

19 Claims, 9 Drawing Sheets



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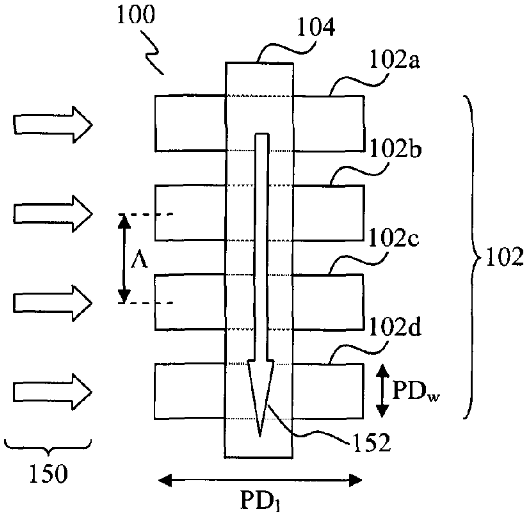

100
104
102a
102b
102c
102d
102
Λ
PD_w
152
150
PD_l

FIG. 1

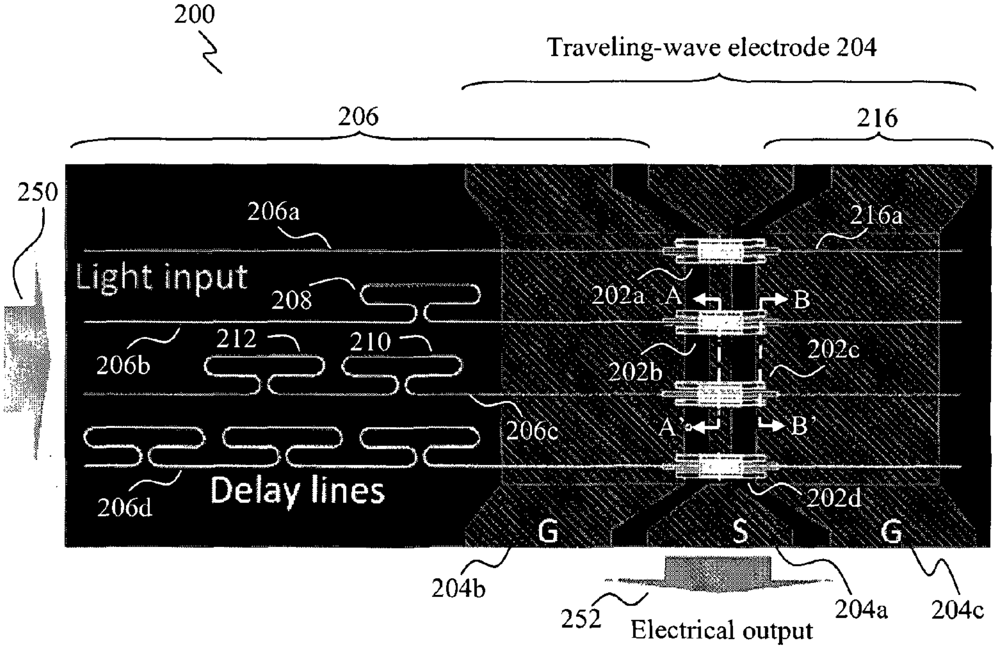

200
Traveling-wave electrode 204
206
216
250
206a
216a
Light input
208
202a
A
B
206b
212
210
202b
202c
206c
A'
B'
206d
Delay lines
202d
G
S
G
204b
252
Electrical output
204a
204c

FIG. 2A

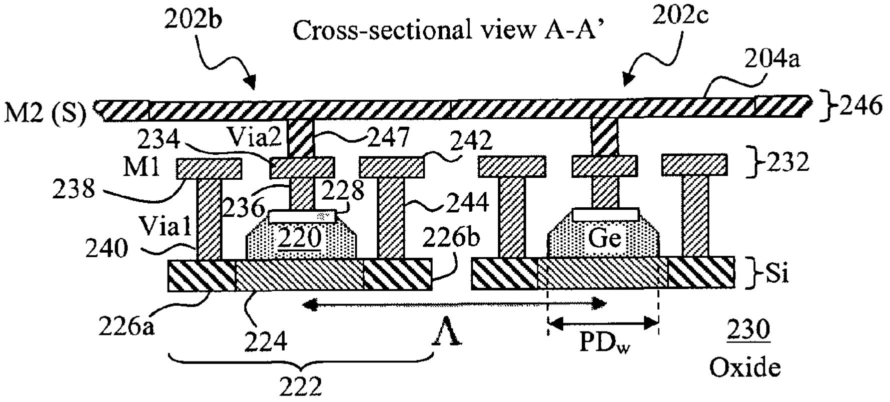

202b
Cross-sectional view A-A'
202c
204a
M2 (S)
246
234
Via2
247
242
M1
232
238
236
228
244
Via1
220
Ge
240
226b
Si
226a
224
Λ
PDw
230
Oxide
222

FIG. 2B

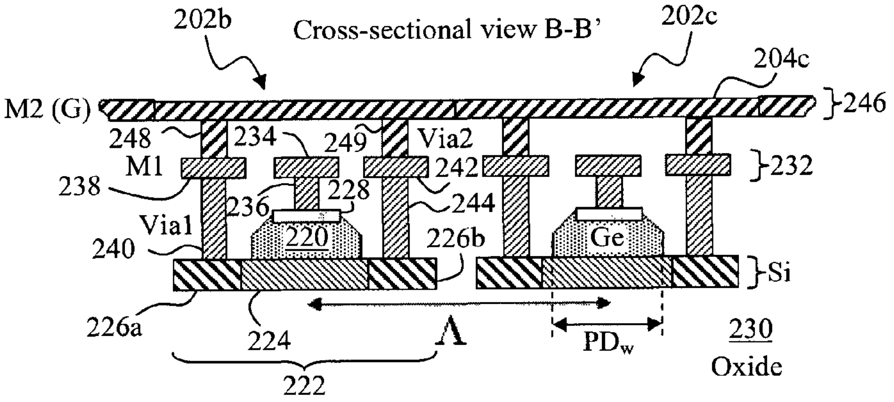

202b
Cross-sectional view B-B'
202c
204c
M2 (G)
246
248
234
249
Via2
M1
242
232
238
228
236
244
Via1
220
Ge
240
226b
Si
226a
224
Λ
PDw
230
Oxide
222

FIG. 2C

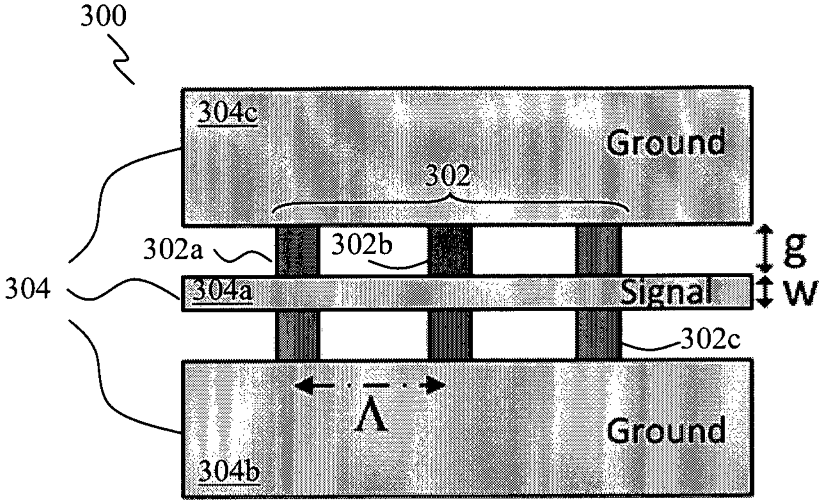

300
304c
Ground
302
302a
302b
g
304
304a
Signal
w
302c
Λ
Ground
304b

FIG. 3A

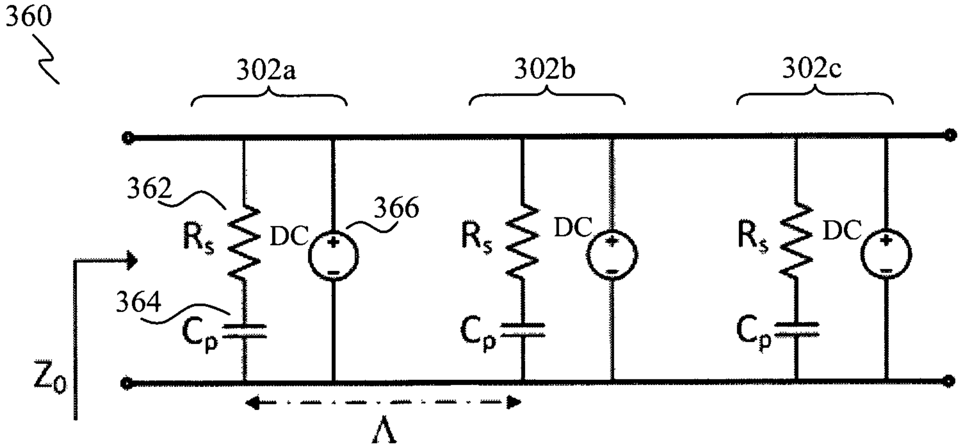

360
302a
302b
302c
362
366
R_s
DC
R_s
DC
R_s
DC
364
C_p
C_p
C_p
Z_0
Λ

FIG. 3B

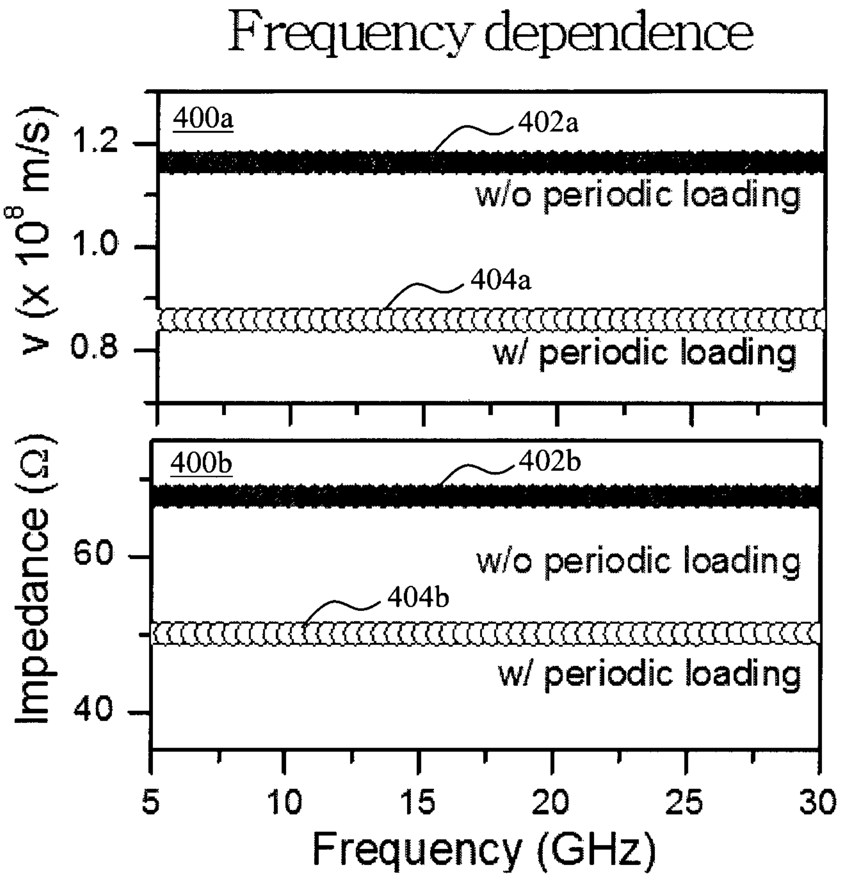

Frequency dependence
400a
402a
w/o periodic loading
404a
w/ periodic loading
v (x 10^8 m/s)
1.2
1.0
0.8
400b
402b
w/o periodic loading
404b
w/ periodic loading
Impedance (Ω)
60
40
5
10
15
20
25
30
Frequency (GHz)

FIG. 4

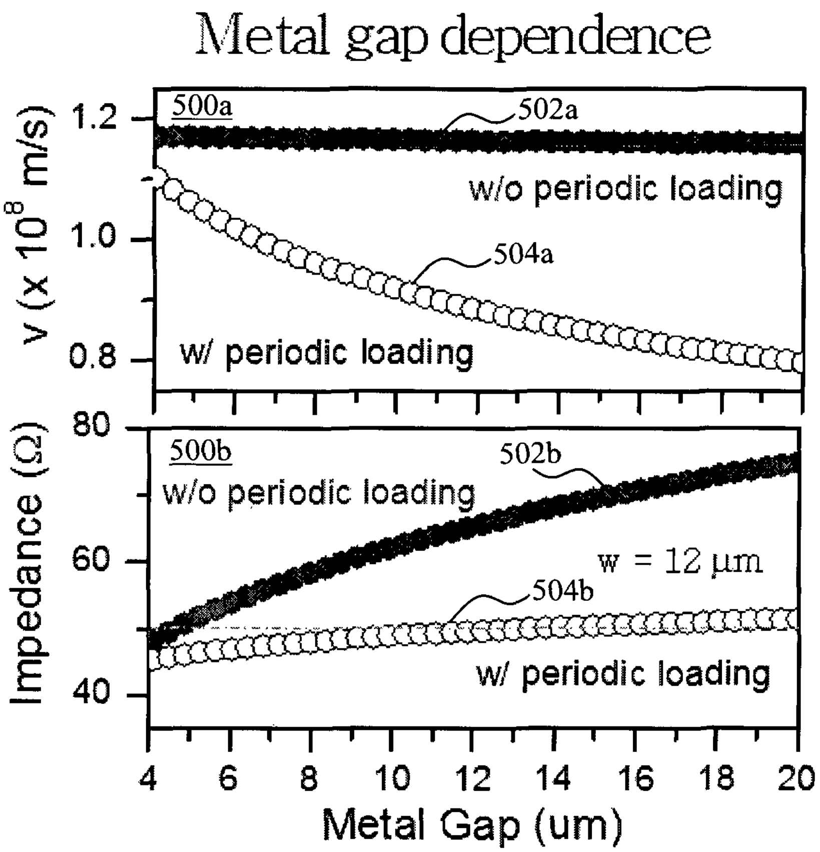

Metal gap dependence
500a
502a
w/o periodic loading
504a
w/ periodic loading
v (x 10^8 m/s)
1.2
1.0
0.8
500b
502b
w/o periodic loading
w = 12 μm
504b
w/ periodic loading
Impedance (Ω)
80
60
40
4
6
8
10
12
14
16
18
20
Metal Gap (um)

FIG. 5

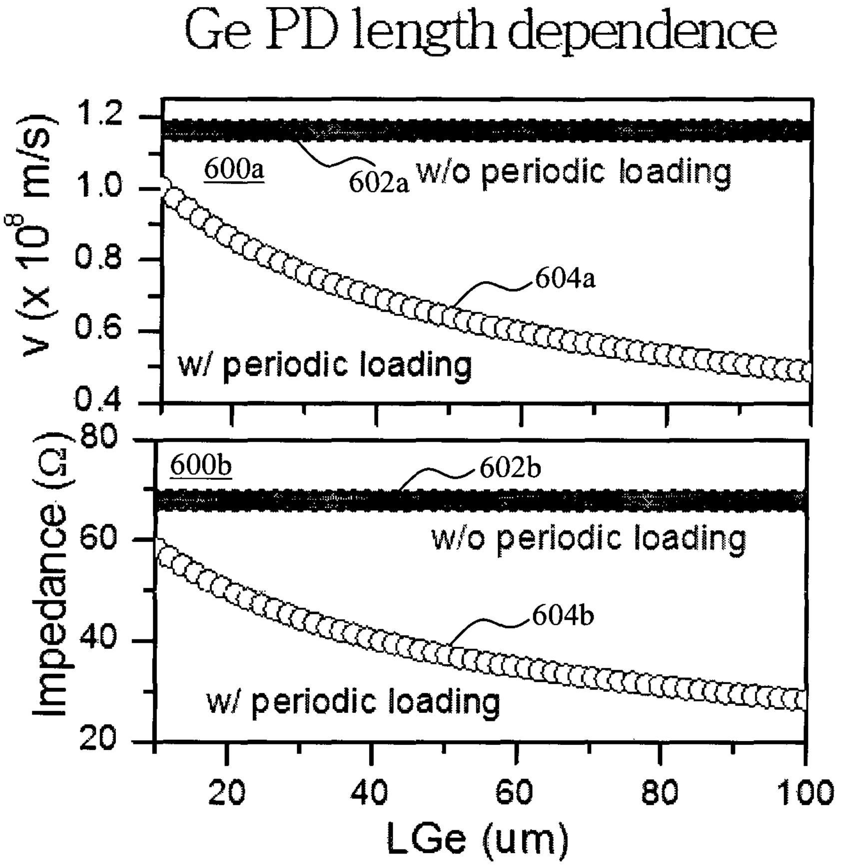

Ge PD length dependence
v (x 10^8 m/s)
1.2
1.0
0.8
0.6
0.4
600a
602a
w/o periodic loading
604a
w/ periodic loading
Impedance (Ω)
80
60
40
20
600b
602b
w/o periodic loading
604b
w/ periodic loading
20
40
60
80
100
LGe (um)

FIG. 6

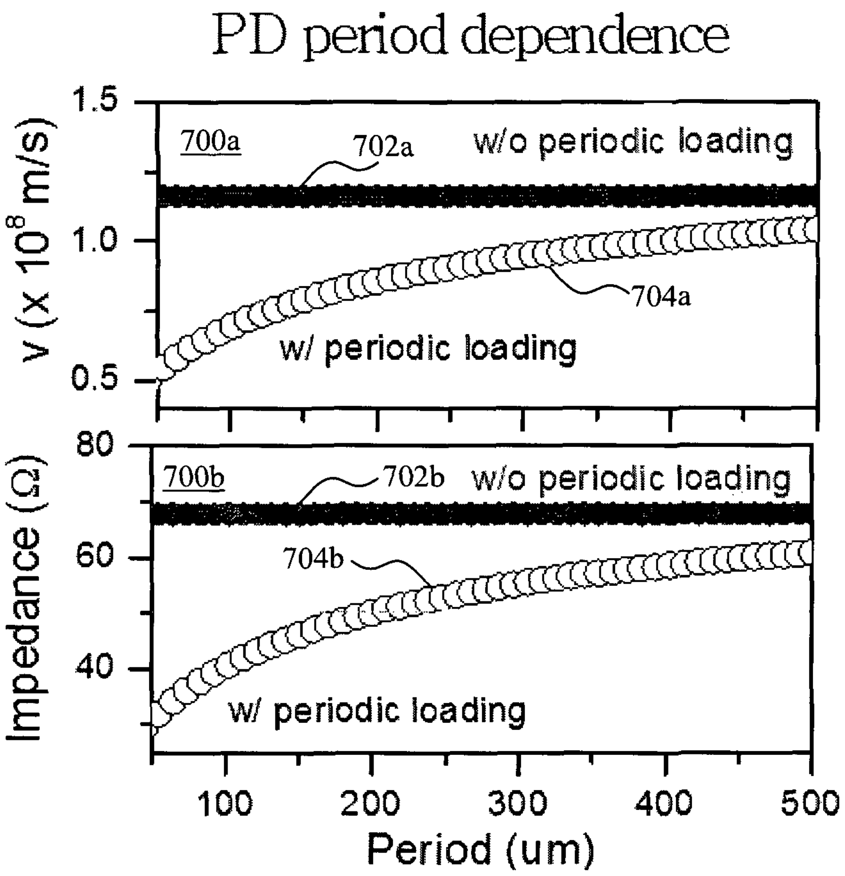

PD period dependence
700a
702a
w/o periodic loading
704a
w/ periodic loading
v (x 10^8 m/s)
1.5
1.0
0.5
700b
702b
w/o periodic loading
704b
w/ periodic loading
Impedance (Ω)
80
60
40
100
200
300
400
500
Period (um)

FIG. 7

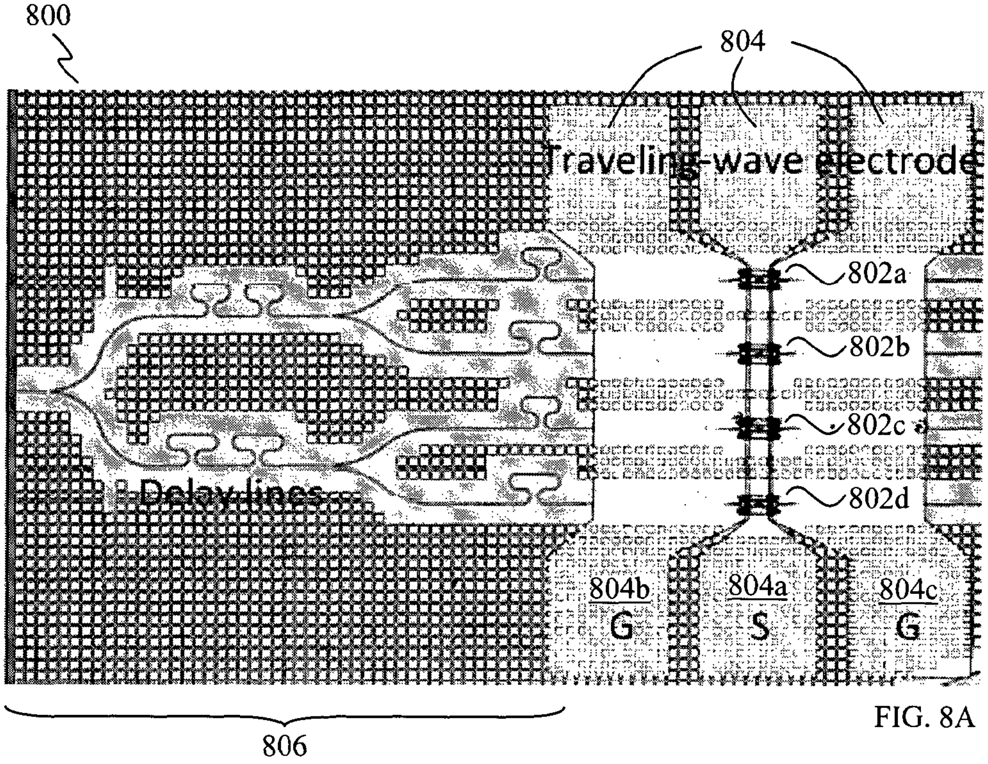

800
804
Traveling-wave electrode
802a
802b
802c
802d
Delay lines
804b
G
804a
S
804c
G
806

FIG. 8A

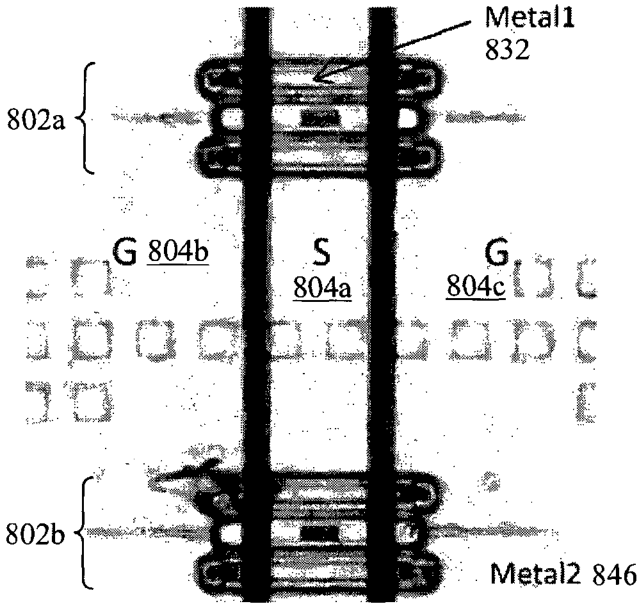
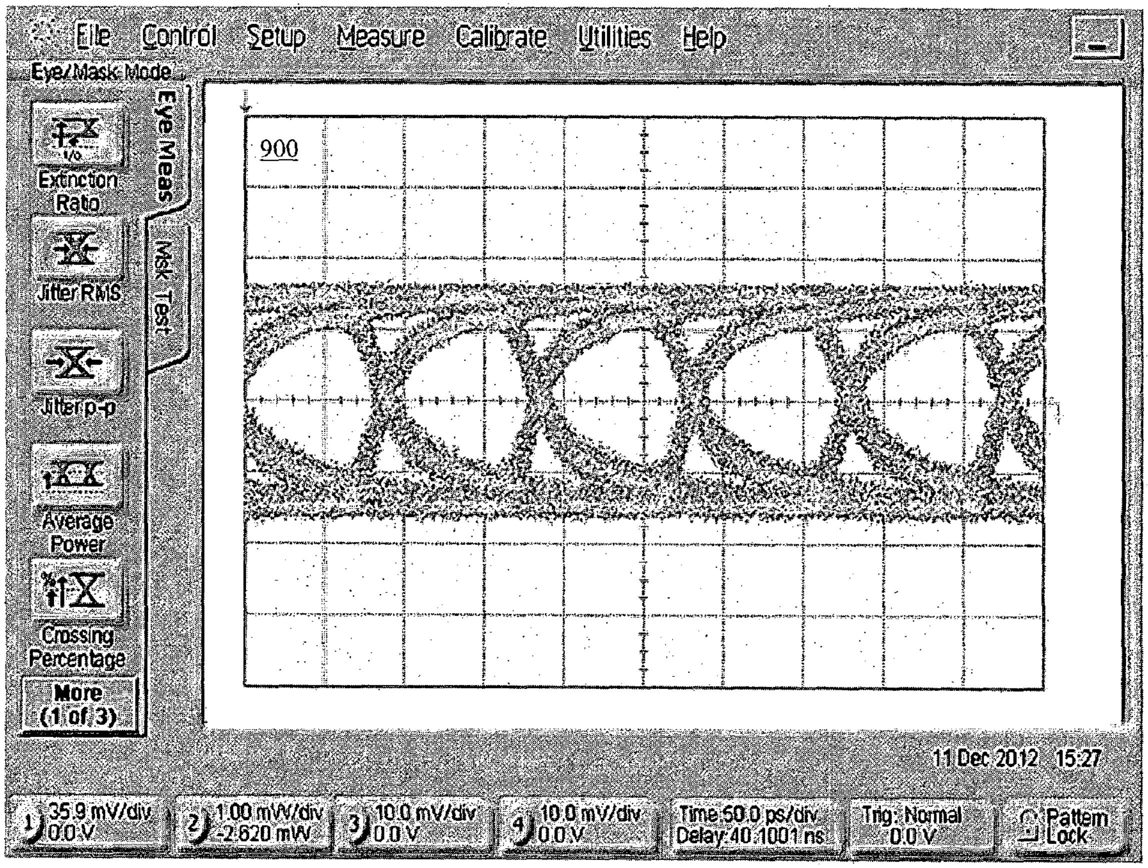

Metal1
832
802a
G 804b
S
804a
G
804c
802b
Metal2 846

FIG. 8B



11 Dec 2012 15:27

1 35.9 mV/div 0.0 V
2 1.00 mW/div -2.620 mW
3 10.0 mV/div 0.0 V
4 10.0 mV/div 0.0 V
Time 50.0 ps/div Delay 40.1001 ns
Trig: Normal 0.0 V

FIG. 9

PHOTODETECTOR ARRANGEMENT

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of priority of Singapore patent application No. 201300749-7, filed 30 Jan. 2013, the content of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

Various embodiments relate to a photodetector arrangement.

BACKGROUND

A germanium-on silicon (Ge-on-Si) photodetector is a key building block for optical interconnect and microwave photonics. A high-power and high-speed photodetector is particularly important for analog optical link with high gain, low noise floor, and high spurious-free dynamic range. However, there is a trade-off between the photodetector operation bandwidth and its saturation power. In general, a photodetector with high speed is usually designed with a low capacitance and a small carrier transit time, thus resulting in small dimensions. This causes the saturation power to be low due to the space charge effect. For conventional photodetectors, it is difficult to work at high speed with a high saturation power. Currently, a Ge photodetector is usually provided with only ~5 mW saturation power and ~10 GHz bandwidth.

SUMMARY

According to an embodiment, a photodetector arrangement is provided. The photodetector arrangement may include a plurality of germanium-based photodetectors, each germanium-based photodetector configured to receive an optical signal and to generate an electrical signal in response to the received optical signal, and an electrode arrangement arranged to conduct the electrical signals.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. **1** shows a schematic top view of a photodetector arrangement, according to various embodiments.

FIG. **2**A shows a schematic design layout of a photodetector arrangement, according to various embodiments.

FIG. **2**B shows a schematic cross-sectional view of the photodetector arrangement of the embodiment of FIG. **2**A, taken long the line A-A'.

FIG. **2**C shows a schematic cross-sectional view of the photodetector arrangement of the embodiment of FIG. **2**A, taken long the line B-B'.

FIG. **3**A shows a simplified schematic top view of a photodetector arrangement, according to various embodiments.

FIG. **3**B shows an equivalent circuit of the photodetector arrangement of the embodiment of FIG. **3**A.

FIG. **4** shows plots of modelling results of the traveling-wave electrode (TWE) phase velocity and impedance as a function of radio frequency (RF) frequency.

FIG. **5** shows plots of modelling results of the traveling-wave electrode (TWE) phase velocity and impedance as a function of metal gap.

FIG. **6** shows plots of modelling results of the traveling-wave electrode (TWE) phase velocity and impedance as a function of photodetector length.

FIG. **7** shows plots of modelling results of the traveling-wave electrode (TWE) phase velocity and impedance as a function of the periodicity of the photodetectors.

FIG. **8**A shows an optical microscope image of a fabricated 4-channel photodetector arrangement, according to various embodiments.

FIG. **8**B shows an optical microscope image of an enlarged sectional view of the fabricated 4-channel photodetector arrangement of the embodiment of FIG. **8**A.

FIG. **9** shows a plot of results of 10 Gb/s pseudo-random binary sequence (PRBS) data detection using the 4-channel photodetector arrangement of the embodiment of FIG. **8**A.

DETAILED DESCRIPTION

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.

Embodiments described in the context of one of the devices are analogously valid for the other devices.

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.

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.

In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

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.

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

Various embodiments may relate to fields including silicon (Si) photonics (e.g. Si nano/micro-photonics), microwave photonics, and optical communication systems.

Various embodiments may provide an approach for developing a traveling-wave photodetector array (TWPDA) with large bandwidth and high power handling capability. Various embodiments may also provide an approach for developing a cost effective photodetector for a silicon (Si) integrated circuit.

Various embodiments may provide a large-bandwidth, high-power traveling-wave photodetector array. In other words, various embodiments may provide a traveling-wave electrode photodetector array with a high operation bandwidth and a high power handling capability. The traveling-wave electrode photodetector array may be applicable for optical communication and microwave photonics.

Various embodiments may provide a traveling-wave photodetector array or arrangement (TWPDA) with a large-bandwidth and high power handling capability. Such a TWPDA may be based on a germanium-on-silicon (Ge-on-Si) substrate, which may provide the benefit of large-bandwidth operation. The TWPDA may include multiple cascaded germanium (Ge) photodetectors (PDs) with parallel feeds, which may enhance the power handling capacity of the TWPDA. The photocurrent from each Ge PD may be collected by using an impedance matched traveling-wave electrode (TWE) to maintain the operation bandwidth. The phase difference, for example corresponding to optical signals and/or electrical signals, that may be present in the TWPDA may be compensated by a design of one or more optical waveguide delay lines.

Various embodiments may provide a traveling-wave photodetector (PD) structure or arrangement with double metal layers. A velocity and impedance matched coplanar waveguide (CPW) for a traveling-wave electrode (TWE) may be employed in the photodetector arrangement of various embodiments. In various embodiments, optical waveguide delay lines may be employed in the photodetector arrangement for velocity matching between the optical signal and the electrical signal propagating in the photodetector arrangement.

Various embodiments may provide a simple design of a traveling-wave photodetector (PD) array. Various embodiments may enable a cost effective implementation and CMOS compatible fabrication of the photodetector array or arrangement of various embodiments. Further, the photodetector array of various embodiments may be ready for photonic integration for various applications.

Various embodiments may provide a traveling-wave photodetector array (TWPDA) that may be designed to be velocity and impedance matched, taking into consideration the periodic loading effect from each individual Ge photodetector. Thus, the TWPDA may feature the merits of a large operation bandwidth and a high power handling capability. Such a TWPDA may be potentially usable for microwave photonics, among other possible photonic applications.

FIG. **1** shows a schematic top view of a photodetector arrangement **100**, according to various embodiments. The photodetector arrangement **100** includes a plurality of germanium-based photodetectors **102**, each germanium-based photodetector **102** configured to receive an optical signal **150** and to generate an electrical signal **152** in response to the received optical signal **150**, and an electrode arrangement **104** arranged to conduct the electrical signals **152**.

In other words, a photodetector arrangement **100** may be provided. The photodetector arrangement **100** may include an array of photodetectors (PDs) **102**, where each PD **102** may include a germanium (Ge)-based material. For illustration purposes, four germanium-based photodetectors (Ge PDs) are shown in FIG. **2**, including a first Ge PD **102***a*, a second Ge PD **102***b*, a third Ge PD **102***c* and a fourth Ge PD **102***d*. However, it should be appreciated that the photodetector arrangement **100** may include two, three, four, five or any higher number of Ge photodetectors **102**. Each Ge PD **102***a*, **102***b*, **102***c*, **102***d* may receive an optical signal (e.g. light) **150** at its input and consequently may produce an electrical signal (e.g. a photocurrent) **152** at its output. The germanium (Ge)-based material of each Ge PD **102***a*, **102***b*, **102***c*, **102***d* may act as an optical or light absorbing portion. The photodetector arrangement **100** may further include an electrode arrangement **104** for conducting the electrical signals **152** generated by the plurality of Ge PDs **102**. This may mean that the electrode arrangement **104** may be electrically coupled to each Ge PD **102***a*, **102***b*, **102***c*, **102***d*, where the electrode arrangement **104** may be adapted to propagate the electrical signals **152**, or in other words, the electrical signals **152** may travel or flow through the electrode arrangement **104**. Further, this may mean that the plurality of Ge PDs **102** may be electrically coupled to each other by means of the electrode arrangement **104**. The electrical signal **152** from each Ge PD **102***a*, **102***b*, **102***c*, **102***d* may be combined by the electrode arrangement **104** into a single output.

In the context of various embodiments, each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may receive the same optical signal **150**.

In various embodiments, the electrode arrangement **104** may include a traveling-wave electrode (TWE) arrangement. This may mean that the photodetector arrangement **100** may be a traveling-wave photodetector array or arrangement (TWPDA). The traveling-wave electrode (TWE) arrangement may act as a transmission line for the electrical signals **152**.

The traveling-wave electrode arrangement may include a coplanar waveguide (CPW). The coplanar waveguide may include three electrodes, in the form of a signal (S) electrode and two ground (G) electrodes arranged adjacent to the signal electrode. The two ground electrodes may be arranged on opposite sides of the signal electrode and spaced apart from the signal electrode. The signal electrode and the two ground electrodes may be located on a same plane, and hence coplanar. This may mean that the signal electrode and the two ground electrodes may be arranged on a same side, for example with reference to a substrate. In various embodiments, the signal (S) electrode and the two ground (G) electrodes may be arranged at least substantially parallel to each other.

In various embodiments, the coplanar waveguide may include a signal (S) electrode electrically coupled to the plurality of germanium-based photodetectors **102** to conduct the electrical signals **152**, and two ground (G) electrodes arranged on opposite sides of the signal (S) electrode and spaced apart from the signal (S) electrode. The signal electrode may conduct the respective electrical signals **152** generated by the plurality of germanium-based photodetectors **102**. The signal electrode may be electrically coupled to the light absorbing portion of each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. The two ground electrodes may be electrically coupled to respective contact regions of each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. In various embodiments, the plurality of germanium-based photodetectors **102** may be arranged successively or sequentially along a length of the signal electrode.

In the context of various embodiments, the signal electrode may have a width, w, of between about 2 μm and about 20 μm, for example between about 2 μm and about 10 μm, between about 2 μm and about 5 μm, between about 5 μm and about 20 μm, between about 10 μm and about 20 μm, or between about 5 μm and about 10 μm.

In the context of various embodiments, a spacing, g, between the signal electrode and each of the two ground electrodes may be between about 1 μm and about 200 μm, for example between about 1 μm and about 100 μm, between about 1 μm and about 50 μm, between about 100 μm and about 200 μm, or between about 50 μm and about 100 μm.

In the context of various embodiments, the electrode arrangement **104** may include a first conductive layer defined into a plurality of contacts, a respective contact being electrically coupled to a respective germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* of the plurality of germanium-based photodetectors **102** and electrically isolated from the other contacts of the plurality of contacts, and a second conductive layer electrically coupled to the plurality of contacts. A respective contact may collect an electrical signal **152** from an associated germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. The second conductive layer may form a common contact or electrode to the plurality of contacts, and therefore also to the plurality of germanium-based photodetectors **102**. The second conductive layer may be arranged over the first conductive layer.

In various embodiments, the first conductive layer and the second conductive layer may define a traveling-wave electrode arrangement, for example in the form of a coplanar waveguide (CPW). The second conductive layer may be defined into a signal (S) electrode and two ground (G) electrodes, the signal electrode being electrically coupled to the plurality of contacts defined from the first conductive layer, while the two ground electrodes may be electrically coupled to respective contact regions of each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*.

Each of the first conductive layer and the second conductive layer may be a metal layer. Each of the first conductive layer and the second conductive layer may include a metal including but not limited to aluminum (Al), or copper (Cu). However, it should be appreciated that other metals may be used.

In various embodiments, the photodetector arrangement **100** may further include a plurality of waveguides, wherein a respective waveguide of the plurality of waveguides may be arranged to propagate the optical signal **150** towards or to a respective germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* of the plurality of germanium-based photodetectors **102**. A respective waveguide may be optically coupled to a respective germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. A respective germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may be formed on or over a respective waveguide. Therefore, the photodetector arrangement **100** may include waveguide-based Ge photodetectors. The plurality of waveguides may be on-chip waveguides, e.g. integrated in the photodetector arrangement **100**.

In the context of various embodiments, each waveguide may include silicon (Si). Therefore, the photodetector arrangement **100** may include waveguide-based Ge-on-Si photodetectors.

In various embodiments, a difference in lengths of respective waveguides corresponding to adjacent germanium-based photodetectors of the plurality of germanium-based photodetectors **102** may introduce an optical time delay (or propagation delay) between the adjacent germanium-based photodetectors such that the respective electrical signals **152** generated by the adjacent germanium-based photodetectors are at least substantially in phase (or phase-matched). Therefore, each waveguide may act as an optical delay line for the optical signal **150**. In this way, the optical signal delay between the adjacent germanium-based photodetectors may be at least substantially matched to an electrical signal delay between the adjacent germanium-based photodetectors. Therefore, a velocity matched electrode arrangement **104** may be provided.

In various embodiments, respective optical time delays between respective adjacent germanium-based photodetectors may be at least substantially the same.

In various embodiments, the electrode arrangement **104** may be arranged to conduct the electrical signals **152** in a direction at least substantially perpendicular to a direction of propagation of the optical signal **150** through the respective waveguide.

In the context of various embodiments, an impedance, Z, of the electrode arrangement **104** may be at least substantially matched to at least one electrical parameter of each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. In this way, the loading effect of each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may be taken into consideration for forming an impedance matched electrode arrangement **104**. The at least one electrical parameter may include a resistance, R_s, and/or a capacitance, C_p, of the germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*. Each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may have at least substantially similar resistance and/or capacitance.

In the context of various embodiments, the plurality of germanium-based photodetectors **102** may be arranged one after another (e.g. in series or in cascade) in a direction along the conduction of the electrical signals **152** through the electrode arrangement **104**. This may mean that the plurality of germanium-based photodetectors **102** may be arranged along a length of the electrode arrangement **104**.

In the context of various embodiments, respective electrical signals **152** generated by respective germanium-based photodetectors **102***a*, **102***b*, **102***c*, **102***d* of the plurality of germanium-based photodetectors **102** may be at least substantially in phase.

In the context of various embodiments, each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may be arranged to receive the optical signal **150** in parallel relative to the other germanium-based photodetectors **102***a*, **102***b*, **102***c*, **102***d*. This may mean that the plurality of germanium-based photodetectors **102** may be arranged with parallel feeds of the optical signal **150** to each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d*.

In the context of various embodiments, the plurality of germanium-based photodetectors **102** may be arranged spaced apart from each other. A period or centre-to-centre spacing, Λ, between adjacent germanium-based photodetectors of the plurality of germanium-based photodetectors **102** may be between about a few tens of microns and about a few hundreds of microns, for example between about 20 μm and about 900 μm, between about 20 μm and about 500 μm, between about 20 μm and about 100 μm, between about 50 μm and about 100 μm, between about 500 μm and about 900 μm, or between about 100 μm and about 500 μm.

In the context of various embodiments, each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may have a length, PD_l, of between about a few microns and about a few hundreds of microns, for example between about 5 μm and about 500 μm, between about 5 μm and about 300 μm, between about 5 μm and about 100 μm, between about 50 μm and about 100 μm, between about 100 μm and about 500 μm, or between about 100 μm and about 300 μm.

In the context of various embodiments, each germanium-based photodetector **102***a*, **102***b*, **102***c*, **102***d* may have a width, PD_w, of between about a few microns and about a few tens of microns, for example between about 2 μm and about 50 μm, between about 2 μm and about 30 μm, between about 2 μm and about 10 μm, between about 5 μm and about 10 μm, between about 10 μm and about 30 μm, or between about 10 μm and about 50 μm.

In the context of various embodiments, the photodetector arrangement **100** may further include a substrate, wherein the plurality of germanium-based photodetectors **102** may be formed on the substrate. The substrate may include silicon (Si), e.g. a silicon wafer or a silicon-on-insulator (SOI) wafer. Therefore, a Ge-on-Si photodetector arrangement **100** may be provided.

Various embodiments may provide a photodetector arrangement, e.g. a traveling-wave photodetector array (TWPDA). The traveling-wave photodetector array may include an array of high-speed Ge photodetectors. Multiple-channel optical signal or light may be separately input into each high-speed photodetector. Each high-speed photodetector may generate an electrical signal or photocurrent in response to the received light. The generated photocurrent from each of the photodetector may be collected by a traveling-wave electrode (TWE). The traveling-wave electrode may be designed with an impedance match by considering the periodic loading of the photodetectors. Waveguide delay lines may be adopted for velocity matching between the optical and the electrical signals. Further, the photodetector array may be designed with two metal layers in order to provide an easy design and layout for the traveling-wave electrode.

FIG. **2**A shows a schematic design layout of a photodetector arrangement **200**, according to various embodiments. The photodetector arrangement **200** may be a traveling-wave photodetector array (TWPDA).

The photodetector arrangement **200** may include an array of germanium-based photodetectors or Ge PDs. As a non-limiting example, as shown in FIG. **2**A, the photodetector arrangement **200** may include four Ge PDs, for example a first Ge PD **202***a*, a second Ge PD **202***b*, a third Ge PD **202***c* and a fourth Ge PD **202***d*. The first Ge PD **202***a*, the second Ge PD **202***b*, the third Ge PD **202***c* and the fourth Ge PD **202***d* may be arranged spaced apart relative to each other. Adjacent Ge PDs may be arranged with a periodicity of A. Each of the first Ge PD **202***a*, the second Ge PD **202***b*, the third Ge PD **202***c* and the fourth Ge PD **202***d* may be at least substantially similar, for example in terms of structure and/or dimension(s) and/or material(s).

The photodetector arrangement **200** may further include an array of input waveguides **206** respectively optically coupled to the plurality of Ge PDs for conveying or guiding an optical signal (e.g. light), as represented by the arrow **250**, to the respective Ge PDs. For example, a first input waveguide **206***a* may be optically coupled to the first Ge PD **202***a*, a second input waveguide **206***b* may be optically coupled to the second Ge PD **202***b*, a third input waveguide **206***c* may be optically coupled to the third Ge PD **202***c*, while a fourth input waveguide **206***d* may be optically coupled to the fourth Ge PD **202***d*.

Adjacent input waveguides, e.g. **206***a* and **206***b*, may have different lengths. As shown in FIG. **2**A, a loop **208** may be introduced in the second input waveguide **206***b*, thereby introducing a delay line length, and consequently a time delay, as compared to the first input waveguide **206***a*. In this way, the optical signal **250** propagating through the second input waveguide **206***b* may arrive at the second Ge PD **202***b* at a delayed or later time (e.g. by a time difference, t_{diff}) as compared to the optical signal **250** arriving at the first Ge PD **202***a* via the first input waveguide **206***a*. Further, two loops **210**, **212** may be introduced as delay line lengths in, the third input waveguide **206***c*. Each of the loops **210**, **212** may have a length that is at least substantially similar to the length of the loop **208**. Therefore, the time difference for the arrival of the optical signal **250** at the third Ge PD **202***c* as compared to the second Ge PD **202***b* may be t_{diff}, while the time difference for the arrival of the optical signal **250** at the third Ge PD **202***c* as compared to the first Ge PD **202***a* may be $2t_{diff}$. Accordingly, the plurality of input waveguides **206** may be waveguide delay lines, acting as optical delay lines. In this way, a respective time delay for the propagation of the optical signal **250** to the respective Ge PDs **202***a*, **202***b*, **202***c*, **202***d* may be introduced for successive Ge PDs **202***a*, **202***b*, **202***c*, **202***d*. The plurality of waveguide delay lines **206** may provide identical delay incremental between successive adjacent input waveguides, e.g. between **206***a* and **206***b*, between **206***b* and **206***c* and between **206***c* and **206***d*.

The photodetector arrangement **200** may further include a plurality of output waveguides **216** respectively optically coupled to the plurality of Ge PDs for outputting at least a portion of the optical signal **250**. For example, a first output waveguide **216***a* may be optically coupled to the first Ge PD **202***a*.

The photodetector arrangement **200** may further include a coplanar waveguide (CPW) as a traveling-wave electrode **204**. The traveling-wave electrode **204** may be electrically coupled to the plurality of Ge PDs. The traveling-wave electrode **204**, in the form of the CPW, may include a source (S) electrode **204***a* and a pair of ground (G) electrodes (e.g. a first ground (G) electrode **204***b* and a second ground (G) electrode **204***c*). The first ground (G) electrode **204***b* and the second ground (G) electrode **204***c* may be arranged on opposite sides of the source (S) electrode **204***a*. Each of the first ground (G) electrode **204***b* and the second ground (G) electrode **204***c* may be arranged spaced apart from the source (S) electrode **204***a*. This may mean that the first ground (G) electrode **204***b* and the second ground (G) electrode **204***c* may be physically separated and electrically isolated from the source (S) electrode **204***a*.

As the optical signal **250** is received or detected by the respective Ge PDs **202***a*, **202***b*, **202***c*, **202***d*, in response, each Ge PD **202***a*, **202***b*, **202***c*, **202***d* may generate an electrical signal (e.g. a current, e.g. a photocurrent), as represented by the arrow **252**, which may be conducted via the source (S) electrode **204***a*. Each of the first ground (G) electrode **204***b* and the second ground (G) electrode **204***c* may act as a common return path for an electrical current (e.g. the electrical signal **252**) in the CPW **204**. The electrical signal **252** may provide an indication of a parameter (e.g. intensity) associated with the optical signal **250**. In various embodiments, a circuit (not shown) may be provided to receive the electrical signal **252**. Such a circuit may be provided internally as part of the photodetector arrangement **200**. The electrical signal **252** may be processed by means of the circuit.

As a result of the time delay associated with the arrival of the optical signal **250** at adjacent Ge PDs, there is a corresponding time delay in the generation of the respective electrical signals **252** by the adjacent Ge PDs. For example, there may be a time delay in the generation of the electrical signal **252** by the second Ge PD **202***b* so as to compensate for the time required for the propagation or conduction of the electrical signal **252** generated by the first Ge PD **202***a* from the first Ge PD **202***a* to the second Ge PD **202***b*. In this way, there may be a velocity matching between the optical **250** and the electrical **252** signals. As a result, respective electrical signals **252** generated by the Ge PDs **202***a*, **202***b*, **202***c*, **202***d* may be at least substantially in phase.

In various embodiments, the traveling-wave electrode **204** may be designed with an impedance match by considering the periodic loading of the photodetectors (PDs) **202***a*, **202***b*, **202***c*, **202***d*. With optimization, each of the Ge PDs **202***a*, **202***b*, **202***c*, **202***d* may operate with a bandwidth that may be larger than approximately 10 GHz. With the traveling-wave electrode design, the operation bandwidth of such TWPDA or photodetector arrangement **200** may maintain the operation bandwidth as that of each individual Ge PD **202***a*, **202***b*, **202***c*, **202***d*.

In order to compensate for the phase difference between each PD **202***a*, **202***b*, **202***c*, **202***d* induced by the traveling-wave electrode **204**, the respective waveguide delay lines **206***a*, **206***b*, **206***c*, **206***d* for each input channel may be suitably designed and optimized.

FIGS. 2B and 2C show schematic cross-sectional views of the photodetector arrangement **200**, illustrating the TWPDA design, taken long the lines A-A' and B-B' respectively indicated in FIG. **2**A. As shown in FIGS. **2**B and **2**C, the second Ge PD **202***b* and the third Ge PD **202***c* may be arranged at a spacing or period indicated as Λ. Each of the second Ge PD **202***b* and the third Ge PD **202***c* may have a width, PD_w, as illustrated in FIGS. **2**B and **2**C, and a length, PD_1. FIGS. **2**B and **2**C illustrate cross-sectional views of a design of the photodetector arrangement **200** with two metal layers **232**, **246** which will be described later below. In order to provide for an easy layout and impedance matching of the traveling-wave electrode **204**, the CPW, as the traveling-wave electrode **204**, may be arranged in a direction orthogonal to the input waveguides **206***a*, **206***b*, **206***c*, **206***d*, and two metal layers **232**, **246** may be introduced.

Using the second Ge PD **202***b* as an example, although similar descriptions may apply to the other Ge PDs of the photodetector arrangement **200**, the second Ge PD **202***b* may include a germanium (Ge) material portion **220** on a silicon (Si) substrate **222**. The germanium (Ge) material portion **220** may be a light absorbing portion for absorbing at least a portion of the optical signal or light **250**. Thus, the second Ge PD **202***b* may be constructed using a Ge-on-Si platform. The silicon (Si) substrate **222** may include a core region **224**, and a first contact region **226***a* and a second contact region **226***b* arranged on opposite sides of the core region **224**. The core region **224** may be a lightly doped region (e.g. a P+ doped region), while each of the first contact region **226***a* and the second contact region **226***b* may be a heavily doped region (e.g. a P++ doped region). The core region **224** may be optically coupled to the second input waveguide **206***b*. A contact portion **228** may be provided electrically coupled to the Ge material portion **220**. The contact portion **228** may be a heavily doped portion (e.g. an N++ doped portion) of a conductivity type that is opposite to that of the substrate **222**. In various embodiments, the plurality of Ge PDs, including the second Ge PD **202***b* and the third Ge PD **202***c*, may be embedded in an insulating layer (e.g. an oxide layer, e.g. SiO_2) **230**. The insulating layer **230** may be a buried oxide (BOX).

A first metal (M1) layer **232** may be provided electrically coupled to the plurality of Ge PDs, including the second Ge PD **202***b* and the third Ge PD **202***c*, of the photodetector arrangement **200**, for example by means of a plurality of conductive vias (e.g. Vias1). The first metal layer **232** may be defined into a plurality of contacts **234**, where a respective contact **234** may be electrically coupled to a respective Ge material portion **220**, by means of a respective via **236**. Each contact **234** may be electrically isolated from each other.

The first metal (M) layer **232** may be further defined into a plurality of first contacts **238**, where a respective first contact **238** may be electrically coupled to a respective first contact region **226***a*, by means of a respective via **240**. The first metal (M) layer **232** may be further defined into a plurality of second contacts **242**, where a respective second contact **242** may be electrically coupled to a respective second contact region **226***b*, by means of a respective via **244**. The plurality of contacts **234**, first contacts **238** and second contacts **242** may be electrically isolated from each other.

A second metal (M2) layer **246** may be provided electrically coupled to the plurality of contacts **234**, the plurality of first contacts **238** and the plurality of second contacts **242**, for example by means of a plurality of conductive vias (e.g. Vias2). The second metal layer **246** may be defined into the source (S) electrode **204***a*, the first ground (G) electrode **204***b* and the second ground (G) electrode **204***c*. As shown in FIG. **2**B, the source (S) electrode **204***a* may be electrically coupled to the plurality of contacts **234**, by means of respective vias **247** to respective contacts **234**. As shown in FIG. **2**C, the second ground (G) electrode **204***c* may be electrically coupled to the plurality of first contacts **238**, by means of respective vias **248** to respective first contacts **238**, and electrically coupled to the plurality of second contacts **242**, by means of respective vias **249** to respective second contacts **242**. It should be appreciated that the arrangement and electrical coupling related to the first ground (G) electrode **204***b* may be analogously based on the descriptions relating to the second ground (G) electrode **204***c*.

As compared to prior art, various embodiments may provide at least one of the following: (1) a velocity and impedance matched traveling-wave electrode design that may allow high-speed operation. Impedance matching may be designed by considering the periodic PD loading effect, while velocity matching may be designed by introducing optical waveguide delay lines; (2) a double metal layer design which may ease the design and layout of the traveling-wave electrode.

A design of the velocity and impedance matched traveling-wave electrode will now be described by way of the following non-limiting example. FIG. **3**A shows a simplified schematic top view of a photodetector arrangement **300**, according to various embodiments, illustrating a traveling-wave photodetector array (TWPDA) having a photodetector (PD) array **302** and a traveling-wave electrode (TWE) **304**. For illustration purposes, as a non-limiting example as shown in FIG. **3**A, the photodetector (PD) array **302** may include three germanium photodetectors (Ge PDs), for example a first Ge PD **302***a*, a second Ge PD **302***b*, and a third Ge PD **302***c*. The first Ge PD **302***a*, the second Ge PD **302***b*, and the third Ge PD **302***c* may be arranged spaced apart from each other with a periodicity of Λ. This means that adjacent Ge PDs may have a centre-to-centre spacing defined by Λ. Each of the first Ge PD **302***a*, the second Ge PD **302***b*, and the third Ge PD **302***c* may have a width, PD_w, and a length, PD_l.

The traveling-wave electrode (TWE) **304** may be in the form of a coplanar waveguide (CPW) having a source (S) electrode **304***a*, and a first ground (G) electrode **304***b* and a second ground (G) electrode **304***c* arranged on opposite sides of the source (S) electrode **304***a*. Each of the first ground (G) electrode **304***b* and the second ground (G) electrode **304***c* may be arranged spaced apart from the source (S) electrode **304***a*, by a distance, g. The source (S) electrode **304***a* may have a width, w. Each of the source (S) electrode **304***a*, the first ground (G) electrode **304***b* and the second ground (G) electrode **304***c* may be formed of a metal layer.

FIG. **3**B shows an equivalent circuit **360** of the photodetector arrangement **300**, taking into consideration the loading effect of the individual PD **302***a*, **302***b*, **302***c*, with parasitic resistor and capacitor. Using the first Ge PD **302***a* as an example, each Ge PD may include a parasitic resistor, R_s, **362** and a parasitic capacitance, C_p, **364** coupled in series, and a DC (direct-current) source **366** coupled in parallel to R_s **362** and C_p **364**.

The dispersion characteristic of the photodetector arrangement **300** may be modelled using the equivalent circuit **360**. Without considering the loading effect of the Ge PDs **302***a*, **302***b*, **302***c*, the effective dielectric constant, $\in_{eff}$, of the CPW **304** may be expressed by Equation 1:

$$\varepsilon_{eff} = \left[\sqrt{\varepsilon_r} + \frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_t}}{1 + \alpha(f/f_{cutoff})^{-b}}\right]^2, \quad \text{(Equation 1)}$$

where $\in_r$ is the dielectric constant of a substrate (e.g. a silicon (Si) substrate), $\in_t$ is the effective dielectric constant of the CPW **304**, taking into consideration the metal thickness, f is frequency, f_{cutoff} is the cutoff frequency of the lowest TE mode propagating through the CPW **304**, and α and b are constants depending on the configurations and dimensions of the CPW **304**.

The phase velocity, v_{ph}, of the CPW **304** without the loading effect may thus be expressed as Equation 2 below:

$$v_{ph} = \frac{c}{\sqrt{\varepsilon_{eff}}}, \quad \text{(Equation 2)}$$

where c is the light speed in vacuum.

The impedance, Z_o, of the CPW **304** may be calculated as

$$Z_o = \frac{K'(k)}{K(k)} \frac{1}{2(\varepsilon_r + 1)\varepsilon_0 v_{ph}}, \quad \text{(Equation 3)}$$

where K(k) and K'(k) are the complete elliptical integrals of the first kind and $\in_o$ is the vacuum permittivity, which equals to $8.8541878176\times10^{-12}$ F/m.

When considering the loading effect with the resistor R_s **362** and the capacitor C_p **364** of a PD **302***a*, **302***b*, **302***c*, the phase velocity, v_L, and the impedance, Z_L, of the CPW **304** may be expressed as

$$v_L = \frac{1}{\sqrt{C_M(f) + \frac{C_{p,eq}}{\Lambda}}} \frac{1}{\sqrt{L_M(f)}}, \quad \text{(Equation 4)}$$

$$Z_L = \frac{\sqrt{L_M(f)}}{\sqrt{C_M(f) + \frac{C_{p,eq}}{\Lambda}}}, \quad \text{(Equation 5)}$$

where the parameters C_M, L_M are the equivalent capacitance and inductance per unit length of the CPW **304**, $C_{p,eq}$ is the effective capacitance of the photodetector (PD) **302***a*, **302***b*, **302***c* related to R_s **362** and C_p **364**, and Λ refers to the period between adjacent PDs (e.g. between PDs **302***a* and **302***b*, or between PDs **302***b* and **302***c*).

The parameter C_M may be expressed as:

$$C_M(f) = \varepsilon_0 \varepsilon_{eff} \frac{K'(k)}{K(k)}. \quad \text{(Equation 6)}$$

The effective capacitance, $C_{p,eq}$, may be expressed as:

$$\frac{1}{C_{p,eq}} = \frac{1}{C_p} + j\omega R_s. \quad \text{(Equation 7)}$$

Based on the above described numerical model, the phase velocity and the impedance of the CPW or TWE **304** may be calculated and compared, depending on the structure parameters, including the RF (radio frequency) frequency, the CPW dimensions, the photodetector (PD) dimensions, and the periodicity.

FIG. **4** shows plots **400***a*, **400***b* of modelling results of the traveling-wave electrode (TWE) phase velocity, v, and impedance as a function of radio frequency (RF) frequency, f. The modelled results **402***a*, **402***b* correspond to a standalone CPW, without the photodetector loading effect, while the modelled results **404***a*, **404***b* correspond to a CPW with the photodetector loading effect.

FIG. **5** shows plots **500***a*, **500***b* of modelling results of the traveling-wave electrode (TWE) phase velocity, v, and impedance as a function of metal gap. The term "metal gap" refers to the spacing, g, between a source (S) electrode and a ground (G) electrode of the TWE. The modelled results **502***a*, **502***b* correspond to a standalone CPW, without the photodetector loading effect, while the modelled results **504***a*, **504***b* correspond to a CPW with the photodetector loading effect. The modelled results **502***b*, **504***b* for the impedance are obtained for a source electrode width, w, of about 12 μm.

FIG. **6** shows plots **600***a*, **600***b* of modelling results of the traveling-wave electrode (TWE) phase velocity, v, and impedance as a function of photodetector length. The modelled results **602***a*, **602***b* correspond to a standalone CPW, without the photodetector loading effect, while the modelled results **604***a*, **604***b* correspond to a CPW with the photodetector loading effect.

FIG. **7** shows plots **700***a*, **700***b* of modelling results of the traveling-wave electrode (TWE) phase velocity, v, and impedance as a function of the periodicity, Λ, of the photodetectors. The modelled results **702***a*, **702***b* correspond to a standalone CPW, without the photodetector loading effect, while the modelled results **704***a*, **704***b* correspond to a CPW with the photodetector loading effect.

As may be observed in FIGS. **4** to **7**, the photodetector loading effect may induce significant deviations or modifications from the standalone CPW. Referring to FIGS. **4** and **5**, there may be a small variation of both velocity and impedance with the RF frequency, while there may be a large variation as a function of the CPW metal gap, for example when the loading effect is present. Referring to FIGS. **6** and **7**, both the Ge PD length and the period, Λ, may affect the velocity and impedance significantly for a CPW with a loading effect.

As both the phase velocity and the impedance may be dependent on the design parameters, the TWPDA may be carefully designed and optimised. For example, the velocity and impedance matched traveling PD array may be designed taking into consideration one or more parameters such as the Ge photodetector width, the Ge photodetector length, the period between adjacent Ge photodetetcors and the CPW width and gap.

Based on the loading periodicity, Λ, and the phase velocity, v, the time difference between the respective photocurrents generated from adjacent photodetectors may be calculated, and subsequently, the respective optical delay lines in each input channel may be determined in order to compensate for the time difference. Thus, the photocurrent that reaches the output point from each individual PD may have identical phases and thus may be phase matched.

Demonstration of a photodetector arrangement or TWPDA on a silicon chip will now be described. A designed TWPDA was fabricated using a CMOS-compatible fabrication process on an 8" silicon-on-insulator (SOI) wafer. The TWPDA may be designed with velocity matching between the optical and the electrical signals. The TWPDA may be designed with impedance matching in terms of the traveling-wave electrode.

FIG. **8**A shows an optical microscope image of a fabricated 4-channel photodetector arrangement (4-channel TWPDA) **800**, while FIG. **8**B shows an optical microscope image of an enlarged sectional view of the fabricated 4-channel photodetector arrangement **800**. The 4-channel photodetector arrangement **800** includes four high-speed Ge PDs **802***a*, **802***b*, **802***c*, **802***d*, two metal layers **832**, **846**, an impedance-matched traveling-wave electrode **804** having a source (S) electrode **804***a*, a first ground (G) electrode **804***b* and a second ground (G) electrode **804***c*, and balanced optical delay lines **806**. In such a design, the gap spacing and the strip line width corresponding to the traveling-wave electrode **804** may be designed freely, avoiding any layout problem.

FIG. **9** shows a plot **900** of results of 10 Gb/s pseudo-random binary sequence (PRBS) data detection using the 4-channel photodetector arrangement **800**, illustrating the high-quality detection of the 10 Gb/s PRBS data. Approximately 1 ps electrical unit delay was measured for the travelling-wave electrode **804**.

As described above, the photodetector arrangement of various embodiments may include a cascade of N high-speed Ge photodetectors, which may be electrically connected by a coplanar waveguide (CPW) as a traveling-wave electrode arrangement. The traveling-wave electrode may be provided with velocity and impedance matchings. Two metal layers may be used in order to provide an easy design for the impedance matched traveling-wave electrode. Waveguide-based optical delay lines may be adopted for velocity matching between the optical and the electrical signals.

While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

The invention claimed is:

1. A photodetector arrangement comprising:

a plurality of germanium-based photodetectors, each germanium-based photodetector configured to receive an optical signal and to generate an electrical signal in response to the received optical signal; and

an electrode arrangement arranged to conduct the electrical signals;

wherein the electrode arrangement comprises a traveling-wave electrode arrangement.

2. The photodetector arrangement as claimed in claim **1**, wherein the traveling-wave electrode arrangement comprises a coplanar waveguide.

3. The photodetector arrangement as claimed in claim **2**, wherein the coplanar waveguide comprises:

a signal electrode electrically coupled to the plurality of germanium-based photodetectors to conduct the electrical signals; and

two ground electrodes arranged on opposite sides of the signal electrode and spaced apart from the signal electrode.

4. The photodetector arrangement as claimed in claim **3**, wherein the signal electrode has a width of between about 2 μm and about 20 μm.

5. The photodetector arrangement as claimed in claim **3**, wherein a spacing between the signal electrode and each of the two ground electrodes is between about 1 μm and about 200 μm.

6. The photodetector arrangement as claimed in claim **1**, wherein the electrode arrangement comprises:

a first conductive layer defined into a plurality of contacts, a respective contact being electrically coupled to a respective germanium-based photodetector of the plurality of germanium-based photodetectors and electrically isolated from the other contacts; and

a second conductive layer electrically coupled to the plurality of contacts.

7. The photodetector arrangement as claimed in claim **1**, further comprising:

a plurality of waveguides, wherein a respective waveguide of the plurality of waveguides is arranged to propagate the optical signal towards a respective germanium-based photodetector of the plurality of germanium-based photodetectors.

8. The photodetector arrangement as claimed in claim **7**, wherein each waveguide comprises silicon.

9. The photodetector arrangement as claimed in claim **7**, wherein a difference in lengths of respective waveguides corresponding to adjacent germanium-based photodetectors of the plurality of germanium-based photodetectors introduces an optical time delay between the adjacent germanium-based photodetectors such that the respective electrical signals generated by the adjacent germanium-based photodetectors are at least substantially in phase.

10. The photodetector arrangement as claimed in claim **7**, wherein the electrode arrangement is arranged to conduct the electrical signals in a direction at least substantially perpendicular to a direction of propagation of the optical signal through the respective waveguide.

11. The photodetector arrangement as claimed in claim **1**, wherein an impedance of the electrode arrangement is at least substantially matched to at least one electrical parameter of each germanium-based photodetector.

12. The photodetector arrangement as claimed in claim **1**, wherein the plurality of germanium-based photodetectors are arranged one after another in a direction along the conduction of the electrical signals through the electrode arrangement.

13. The photodetector arrangement as claimed in claim **1**, wherein respective electrical signals generated by respective germanium-based photodetectors of the plurality of germanium-based photodetectors are at least substantially in phase.

14. The photodetector arrangement as claimed in claim **1**, wherein each germanium-based photodetector is arranged to receive the optical signal in parallel relative to the other germanium-based photodetectors.

15. The photodetector arrangement as claimed in claim **1**, wherein the plurality of germanium-based photodetectors are arranged spaced apart from each other.

16. The photodetector arrangement as claimed in claim **15**, wherein a period between adjacent germanium-based photodetectors of the plurality of germanium-based photodetectors is between about 20 μm and about 900 μm.

17. The photodetector arrangement as claimed in claim **1**, wherein each germanium-based photodetector has a length of between about 5 μm and about 500 μm.

18. The photodetector arrangement as claimed in claim **1**, wherein each germanium-based photodetector has a width of between about 2 μm and about 50 μm.

19. The photodetector arrangement as claimed in claim **1**, further comprising a substrate, wherein the plurality of germanium-based photodetectors are formed on the substrate.

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