

"Double photodiode electromagnetic radiation sensor device"

DESCRIPTION

TECHNICAL FIELD

5 The present invention relates to electromagnetic radiation sensors of the double photodiode type.

STATE OF THE ART

Double photodiode electromagnetic radiation sensors allow the detection of an optical signal in two different spectral bands.

10 The first demonstration of how the use of two photodiodes in a back-to-back configuration allows the detection of an optical signal in two different spectral bands is reported in the article J.C. Campbell et al. "Dual-wavelength demultiplexing InGaAsP photodiode," Applied Physics Letters 34, 401 (1979).

15 This paper describes the use of two layers of InGaAsP (with different concentrations of the individual chemical elements) as photosensitive elements in the 0.8-1.1 μm and 1.0-1.3 μm bands. The structure is deposited on an InP substrate and has three independent metal contacts.

20 The paper E.R. Blazejewski et al, "Bias switchable dual band HgCdTe infrared photodetector," J. Vac. Sci. Tech. B, 10, 1626 (1992) describes a back-to-back configuration used to manufacture a mid-infrared and far-infrared active optical sensor using two HgCdTe alloys deposited on a CdZnTe substrate as active layers. In this case the device is photosensitive in the 2-4.3 μm and 4.5-8.2 μm bands.

25 Paper L. Colace et al, "Solid state wavemeter with InGaAsP/InGaAs two-diode heterostructure," Electronics Letters 38,735 (2002) describes a back-to-

back structure using two layers of InGaAsP with different band gaps deposited on InP to measure the wavelength of a laser in the 30 nm range.

Document US-A-6342720 describes a photodetector comprising a double diode consisting of a silicon Schottky diode and a PIN-type SiGe diode.

5 Document US-A-6043517 discloses a photodetector that operates for two wavelength ranges and comprises two detectors arranged one above the other. A silicon Schottky diode forms a first detector that absorbs light with wavelengths shorter than 0.9 μm . A second detector (a Si/SiGe diode) absorbs light with wavelengths greater than 1 μm and less than 2 μm .

10 The paper E. Talamas Simola et al. "Voltage-tunable dual-band Ge/Si photodetector operating in VIS and NIR spectral range" Vol. 27, No. 6; 18/03/2019, OPTICS EXPRESS 8529, describes a device having a germanium-on-silicon epitaxial structure consisting of two photodiodes connected back-to-back and such that it operates as a photodetector for a wide band of wavelengths.

15 SUMMARY OF THE INVENTION

The present invention addresses the problem of providing an electromagnetic radiation sensor, of the two-photodiode type in a back-to-back configuration, which has an alternative structure to the known ones, without being of complex manufacturing and which is compatible with the processing techniques of CMOS electronics allowing, consequently, the integration of the sensor with the electronic control and readout modules of the sensor itself.

20 In accordance with a first aspect, the present invention relates to a double photodiode electromagnetic radiation sensor device as defined in independent

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claim 1 and to particular embodiments thereof as defined in dependent claims 2-13.

According to a second aspect, the present invention has as its object an electromagnetic radiation detection system according to claim 14 and by a particular embodiment thereof, as defined by dependent claim 15.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is hereinafter described in detail, by way of example and not limitation, with reference to the accompanying drawings, in which:

- figure 1 shows the circuit diagram of a two-photodiode sensor device in back-to-back configuration;

- figure 2 shows, as an example, the trend of the current generated by the sensor device as a function of wavelength and regulation voltage;

- figure 3 shows, according to a first embodiment, a cross section of the structure of the sensor device integrated in a substrate of semiconductor material;

- figure 4 shows a plan view of the structure of the sensor device of the first embodiment;

- figure 5 shows, in accordance with a second embodiment, a cross-section of a structure of said sensor device integrated into a substrate of semiconductor material;

- figure 6 shows, in accordance with a third embodiment, a cross-section of a structure of said sensor integrated in a substrate of semiconductor material;

- Figure 7 shows, in accordance with a fourth embodiment, a cross-section of a structure of said sensor integrated in a substrate of semiconductor material;

- Figure 8 shows, in accordance with a fifth embodiment, a cross-section of a structure of said sensor integrated in a substrate of semiconductor material
- Figure 9 schematically shows a spectrum detection system including said sensor device.

5 DETAILED DESCRIPTION

In this description, similar or identical elements or components will be indicated in the drawings by the same identifying symbol.

Figure 1 shows a circuit scheme of a double photodiode sensor device 10 (also referred to herein as "sensor" for brevity). The sensor 10 includes a first photodiode PD1 and a second photodiode PD2 arranged in a "back-to-back" configuration i.e., with cathodes (or anodes) electrically connected to each other. These first and second photodiodes PD1 and PD2 are adjustable by applying a suitable voltage V_B to the remaining anodes (or cathodes).

In particular, the first photodiode PD1 (hereinafter, also referred to as "PD1 diode") is obtained from a semiconductor material with energy gap (i.e., band gap) E_{g1} and the second photodiode PD2, is obtained from another semiconductor material with energy gap $E_{g2} < E_{g1}$.

The first diode PD1 is configured to collect and convert into an electrical signal (i.e., a photocurrent I_{ph}) the radiation with wavelength λ between a first minimum wavelength $\lambda_{min}(PD1)$ and a first maximum wavelength $\lambda_{max}(PD1) = hc/E_{g1}$ (with hc universal constants).

The second photodiode PD2 (hereafter also called "PD2 diode") is configured to collect and convert into an electrical signal (a corresponding photocurrent I_{ph}) the radiation with wavelengths ranging from a second minimum wavelength $\lambda_{min}(PD2)$ to a second maximum wavelength

$\lambda_{\max}(\text{PD2}) = hc/E_{g2}$ with $\lambda_{\min}(\text{PD2}) < \lambda_{\max}(\text{PD1})$.

As an example in the case of silicon, indicative values of $\lambda_{\min}(\text{PD1})$ and $\lambda_{\max}(\text{PD1})$ are 400 nm and 1100 nm, respectively, and in the case of germanium, indicative values of $\lambda_{\min}(\text{PD2})$ and $\lambda_{\max}(\text{PD2})$ are 400 nm and 1800 nm, respectively.

An exemplary embodiment of the sensor structure 10 is illustrated in Figures 3 and 4 (in which the various layers represented are not necessarily to scale). In the following description, reference will be made, by way of example, to the materials silicon and germanium.

As shown in Figure 3 and Figure 4, the sensor 10 includes a substrate 25 made of a first semiconductor material (in the example, shown, silicon) having, for example, p-type doping. The substrate 25 defines a first face 30 and an opposing second face 32.

The first face 30 constitutes an exposed region from which the electromagnetic radiation EMR penetrates. Note that the substrate 25 of the sensor 10 in Figure 3 may be n-type.

A first doped region 31 is formed in the substrate 25, of the same material as the substrate, but with a doping opposite to that of the substrate 25 and that is, according to the example, with an n-type doping. The first doped region 31 extends from the second face 32 of the substrate 25 towards the interior of the substrate itself, without reaching, the first face 30.

Note that said first doped region 31 is intended to act as a common electrode (according to the example, a cathode) to the first diode PD1 and the second diode PD2.

A second doped region 33 is formed within the substrate 25 having,

according to the example, a doping of the same type as the substrate 30 but higher, i.e., a p⁺ type doping. The second doped region 33 extends from the second face 32 toward the interior of the substrate 25 without reaching the first face 30, with a depth less than, for example, that of the first doped region 31.

5 For example, the second doped region 33 is developed within the substrate 25 so as to laterally surround, in an open loop, the first doped region 31.

Note that the second doped region 33 is intended to act as an additional electrode (in this example, as an anode) for the first PD1 diode.

10 Further, the sensor 10 includes a layer made of a second semiconductor material 34 (made of germanium, according to the example) placed on the second face 32 of the substrate 25 and so as to be in contact with the first doped region 31. Said germanium layer 34 is, for example, intrinsic germanium. The germanium layer 34 is such as to define a third face 35 opposed to the second
15 face 32.

For example, the intrinsic germanium layer 34 results in facing part of the first doped region 31 (in particular, a central portion thereof), without entirely covering it.

20 Note that, according to the example, the germanium layer 34 is intended to operate as an intrinsic layer of the second PD2 diode.

Over the third face 35 of the intrinsic germanium layer 34 is placed a doped layer 36 (in germanium) having, according to the example, a high p-type doping (i.e., a p⁺ doping). The doped layer 36 is intended to act as an anode for the second diode PD2.

25 The sensor 10 has metal contacts arranged to contact the second doped

region 33 at said second face 32 and the doped layer (36).

In particular, according to the embodiment form of Figure 3, the sensor 10 is provided with a first metal layer 37 arranged above second doped region 33 (i.e., the anode of the first diode PD1), so as to form a first ohmic contact BC.

Further, the sensor 10 includes a second metal layer 38 that forms a second ohmic contact TC electrically connected to the doped layer 36.

According to this first embodiment, the connection between the second ohmic contact TC and the doped layer 36 (i.e., the anode of the second PD2 diode) is made by means of a first high-doped well 39 (i.e., a high-conductivity well) and a second high-doped well 40.

The first high-doped well 39 extends from the second face 32 inwardly into the first doped region 31 (n-type) and has, according to the example, a p⁺ doping. The second ohmic contact TC is disposed on the second face 32 in contact with a portion of the high doping well 39.

The second high-doped well 40 extends, within the germanium layer 34, from the doped layer 36 (with which it is in contact) to the first high-doped well 39 at the second face 32. According to the example, the second high-doped well 40 is made of p⁺ doped germanium.

Summarizing, the first diode PD1 comprises the first doped region 31, a portion of the substrate 25, and the second doped region 33. The second diode PD2 comprises the first doped region 31, the intrinsic germanium layer 34, the doped layer 36, and the first and second high-doped wells 39 and 40.

The sensor 1 can be manufactured using conventional semiconductor material integration techniques that are compatible with CMOS integration

techniques.

For example, the first doped region 31, the second doped region 33, the doped layer 36, the first high dopant well 39, and the second high dopant well 40 may be formed by implantation techniques and/or by spin-on dopant and/or deposition techniques (including epitaxy, sputtering, evaporation).

The intrinsic germanium layer 34 may be formed by chemical and/or physical deposition techniques such as: epitaxy, sputtering, evaporation or even transfer as wafer bonding.

For example, the intrinsic germanium layer 34 may be 500 nm to 3 μm thick. In accordance with the example, the doped layer 36 (i.e., the anode of the second PD2 diode) may be 5 to 200nm thick.

The intrinsic germanium layer 34 is entirely within the first doped region 31 of the silicon substrate 25 and, therefore, it is possible to deposit the intrinsic germanium layer 34 by techniques such as selective deposition (e.g., oxide window deposition), or it is possible to deposit the germanium layer 34 over the entire substrate 25 and then define the geometry of the layer 34 itself by selective removal techniques (photolithography).

The first diode PD1, being made of silicon, is such as to collect and convert into an electrical signal (i.e., the current I_{ph}) the radiation in the visible and near infrared and then the radiation having, indicatively, a minimum wavelength $\lambda_{min}(PD1)$ of 400nm and a maximum wavelength $\lambda_{max}(PD1)$ of 1100 nm. The VIS (Visible) band is, as known, included in the wavelength range 400 nm - 700 nm. The Near InfraRed (NIR) band extends from 700 nm to 1100 nm.

The second diode PD2 made at least partially of germanium, is

configured to collect and convert into an electrical signal (i.e., the current I_{ph}) the radiation having, indicatively, minimum wavelength $\lambda_{min}(PD2)$ 400 nm and maximum wavelength $\lambda_{max}(PD2)$ of 1800 nm.

As known, the near infrared (NIR) band extends from 700 nm to 1100 nm, while the short wave infrared (SWIR) band is included in the wavelength range 1100 nm - 3000 nm.

In other words, the sensor 10, when fabricated using silicon for the PD1 photodiode and germanium for the PD2 photodiode as shown in the particular embodiment form in Figure 3, can operate in the visible, near infrared to part of the short wave infrared.

Regarding the operation of sensor 10, note that the bias voltage V_B is conventionally understood as the voltage difference between the second ohmic contact TC and the first ohmic contact BC. According to this definition, for positive bias voltages V_B , the second diode PD2 biases directly and the first diode PD1 biases inversely, and vice versa for negative voltages V_B .

When the sensor 10 is illuminated on the side of the semiconductor with energy gap E_{g1} (i.e., at the first face 30 of the diode PD1, according to the example), the first photodiode PD1 will absorb the portion of the higher energy light radiation and the second photodiode PD2 will be illuminated by the only light radiation that cannot be absorbed by the gap semiconductor E_{g1} .

The photodiode made with the gap semiconductor E_{g1} (i.e. the first diode PD1) is, therefore, able to generate photocurrent only in the presence of light radiation at low wavelength ($\lambda < hc/E_{g1}$, with hc universal constants) while, on the contrary, the second photodiode PD2 responds only to photons with wavelength λ greater than $\lambda_{max}(PD1)$ and less than $\lambda_{max}(PD2)$:

$$\lambda_{\max}(\text{PD1}) < \lambda < \lambda_{\max}(\text{PD2}).$$

The total photocurrent generated by sensor 10 will be given by the difference between the photocurrents generated by the two different photodiodes PD1 and PD2.

5 This photocurrent I_{ph} can be measured by connecting to the first and second ohmic contacts BC and TC with a corresponding electronic conditioning and acquisition system.

More in detail, when the first diode PD1 is inversely biased it is able to generate the photocurrent I_{ph} when illuminated with radiation with wavelength λ between $\lambda_{\min}(\text{PD1})$ and $\lambda_{\max}(\text{PD1})$, while the second diode PD2 is directly biased and is therefore optically inactive, but allows the circulation of the current I_{ph} .

Vice versa, when the second diode PD2 is reverse biased it is able to generate the photocurrent I_{ph} (if illuminated with radiation wavelength λ between $\lambda_{\max}(\text{PD1})$ and $\lambda_{\max}(\text{PD2})$, while the first diode PD1 is direct biased and is therefore optically inactive, but allows the circulation of the current I_{ph} .

Acting on the bias voltage V_B it is possible to electrically select the spectral response of the sensor 10. Figure 2 shows, as an example, the trend of the current I_{ph} as a function of wavelength, for two extreme values of the bias voltage V_B .

Depending on the applied bias voltage V_B it will be possible to change the collection efficiency of the two junctions associated with the two diodes PD1 and PD2; in particular, as the collection efficiency of the junction with gap E_{g1} increases, it will be observed a decrease in the collection efficiency of the junction with gap E_{g2} and vice versa. This approach allows the responsivity

spectrum of sensor 10 varying continuously.

It should be noted that although silicon and germanium were referred to in the example of Figure 1, the sensor 10 may be manufactured by other semiconductor materials. For example, other possible materials capable of satisfying the aforementioned relationships between the photoresponse bands of the first diode PD1 and/or the second diode PD2 include semiconductor materials chosen from one of the following types:

- a) III-V semiconductors (e.g., GaAs, InAs, InP) and alloys thereof;
- b) II-VI semiconductors (e.g., ZnSe, ZnTe, CdSe, CdTe, HgTe, PbS, PbSe) and their alloys;
- c) IV semiconductors (e.g., Si, Ge, GeSn) and their alloys.

The form of realization of the sensor 10 described above is not complex to manufacture and, in addition, has the advantage of presenting the metal contacts of the sensor on the same side of the substrate 25 in which it is integrated resulting, therefore, of "planar" type.

The flatness of the sensor device 10 allows its monolithic integration on silicon substrates in which there are other electronic circuits made with CMOS processing techniques. In this way it is possible to realize simultaneously the sensor device and the electronic conditioning and acquisition system on the same substrate, using similar processing technologies that represent an industry standard.

Even when only the sensor device is fabricated on a silicon substrate, the presence of metal contacts TC and BC placed on the same face of the device facilitates the subsequent connection of the latter to external circuits and electronic systems for conditioning and acquisition of the photocurrent signal.

In the latter case, the sensor device 10 can be connected to the external circuitry by means of micro-soldering techniques (bump-bonding, wire bonding, Cu-Cu bonding) or through an electronic connection board (PCB), as will also be specified later.

5 Figure 5 refers to a second embodiment of the sensor 10, similar to that of Figures 3 and 4 but in which the second ohmic contact TC is made by means of a metal layer 41 covering the doped layer 36 (p+, Ge) and the second high-doped well 40, contacting the first high-doped well 39 at the second face 32. In this case, the second TC ohmic contact results directly connected to the doped layer 36 and the second high-doped well 40 as well, providing a better distribution of the electric field within the second PD2 photodiode and decreasing the series resistance effects.

10 Figure 6 relates to a third embodiment of sensor 10, similar to that of Figures 3 and 4, but in which the first and second high-doped wells 39 and 40 are not provided. In the embodiment form of figure 6, the second TC ohmic contact is made by means of a fourth metal layer 42 that covers the doped layer 36, resulting in spacing from the second face 32. In this case, the absence of the high doping wells 39 and 40 allows further simplification of the fabrication process of the sensor device.

20 Figure 7 refers to a fourth embodiment of the sensor 10, which is similar to the third embodiment of Figure 6 but in which the second ohmic contact TC is obtained by means of a fifth metal layer 43 that only partially covers the doped layer 36.

25 Furthermore, according to the fourth embodiment of the sensor 10, the first metal layer 37 (forming the first ohmic contact BC) and the fifth metal

layer 43, (forming the second ohmic contact TC) are vertically extended within an insulating layer 44 (e.g., silicon dioxide) arranged to cover part of the second face 32 and part of the doped layer 36.

In particular, the first metal layer 37 and the fifth metal layer 43 form, on
5 a free face 45 of the insulating layer 44, a first contact pad 46 and a second contact pad 47, respectively.

This fourth embodiment allows all the metal contacts to be made at the same height in correspondence with the free face 45; consequently, connection of the sensor device 10 to any external electronic systems is easier due to the
10 absence of differences in height between the various metal contacts.

Figure 8 refers to a fifth embodiment of the sensor 10, similar to the first embodiment in Figure 3 but further comprising a third ohmic contact FC (electrically isolated from the first and second ohmic contacts BC and TC), made by a corresponding metal layer.

15 Said third ohmic contact FC extends on the second face 32 above a third high-doped well 48. The third high-doped well 48 is, according to the example, made of silicon and is made internally to the first doped region 31, presenting a higher doping but of the same type as that of the first doped region 31, i.e., according to the example, an n⁺ doping.

20 The third ohmic contact FC, placed in contact with the first doped region 31 (which acts as a cathode for the first diode PD1 and second diode PD2), offers the advantage of allowing to bias the two photodiodes PD1 and PD2 independently of each other, allowing to acquire two different photocurrent signals, for example: one related to the VIS band (PD1) and the other related
25 to the NIR-SWIR band (PD2).

Regarding the possible uses, the sensor 10 can be employed to realize a camera capable of acquiring images in two different bands (for example, in the VIS-NIR and in the SWIR). In addition, sensor 10 can be used in a spectrum detection system for the purpose of spectral analysis of incident radiation or
5 to realize a hyperspectral imaging sensor system.

For example, for the realization of the two-band imaging camera or the hyperspectral imaging sensor system, a plurality of sensors 10 having a structure similar to that described above can be integrated into the same substrate 25, resulting side-by-side and forming a two-dimensional array.

10 With reference to these possible applications, Figure 9 illustratively shows a spectrum detection system 100 comprising an electromagnetic radiation sensor apparatus 20 and an electronic control and processing module 50. In more detail, the electronic control and processing module 50 is configured to extract and provide on an output OU information related to the
15 spectrum of radiation invading the sensor 10. The electronic control and processing module 50 includes a readout module 2 (RD), a conditioning module 3 (CND), and an analysis and control device 4 (CNT-AN).

According to a first embodiment, described below, the spectrum detection system 100 may be configured to perform spectral analysis of an
20 electromagnetic radiation by providing on the output OU information SP-ANS relating to the measurement of the intensity of the incident radiation as a function of wavelength.

The electromagnetic radiation sensor apparatus 20 includes the sensor device 1. For the purpose of spectral analysis of electromagnetic radiation, the
25 sensor apparatus 20 may include a single sensor 10.

With respect to the control and processing module 50, note that the readout module 2 is configured to convert the current signal I_{ph} to a voltage signal V_{ph} and includes, for example, a trans-impedance amplifier (not shown).

5 The conditioning module 3 is configured to treat the voltage signal V_{ph} so as to make it suitable for subsequent processing. For example, the conditioning module 3 performs operations such as amplification, filtering, level adaptation, dark current cancellation, and an analog-to-digital conversion of the voltage signals V_{ph} to digital values V_{phi} .

10 The analysis and control device 4 is configured to receive digital values V_{phi} representative of the voltage signals V_{ph} , corresponding to the photo-current signals generated by the sensor 10 for various bias voltages V_B , and perform a spectral analysis of the radiation invading the sensor 1. The analysis and control device 4 may include programmable logic (e.g., ASIC/FPGA) configured to perform such a spectral analysis.

15 In addition, the analysis and control device 4 is configured to generate digital voltage values V_{bi} which, through appropriate conditioning (which can be performed by the conditioning module 3) are transformed into analog values of the bias voltage V_B to be applied to the sensor 1 to vary its spectral response.

20 For example, the control and processing module 50 is a ROIC (ReadOut Integrated Circuit) that can be directly integrated into the substrate 25 used to make the sensor 10. Alternatively, the sensor 10 and the ROIC 50 can be made on two different substrates and then connected via bump-bonding or wafer-bonding techniques. Alternatively, sensor 1 and ROIC 50 may be fabricated on
25 different substrates and then connected via a PCB.

As already described, the sensitivity spectrum of sensor 10 can be continuously modified; in particular, several spectral responses intermediate to the extreme ones (obtainable by applying the maximum or minimum bias voltage) shown in Figure 2 can be obtained.

5 This property offers the possibility of obtaining a large number of spectra, dynamically tunable, through the application of the bias voltage V_B and extended in the visible and near-infrared range, allowing the realization of a compact spectral analysis system.

10 Note that the spectral analysis is based on the knowledge of the spectral responsivity of the sensor 10, this spectral responsivity is determined in a characterization step.

15 In accordance with another embodiment of the system 100, the system can be configured to operate as a hyperspectral imaging system, i.e., a hyperspectral imaging system IPST-IM. In this case, the sensor apparatus 20 includes a plurality of sensor devices 10, similar to the sensor described above, organized according to a matrix. For example, the sensor apparatus 20 may include millions of sensors 10 each corresponding to a pixel of the hyperspectral image to be acquired.

20 The electronic control and processing module 50 is, in this case, configured to receive the photocurrents I_{ph} provided by each sensor 1 (corresponding to a pixel) and process them to obtain the hyperspectral image, in which for each pixel the image spectrum of a scene is provided.

25 The Spectrum 100 detection system is used, for example, in the automotive sector (Fog, Night Vision, augmented vision), in the Machine Vision sector (Industry 4.0, increased machine vision) or in the plastics

recycling sector.

LIST OF THE FIGURE NUMBERS

- sensor device 10
- spectrum detection system 100
- 5 - electromagnetic radiation sensor 20
- electronic control and processing module 50
- output OU
- reading module 2
- conditioning module 3
- 10 - analysis and control device 4
- First photodiode PD1
- Second photodiode PD2
- bias voltage V_B
- photocurrent I_{ph}
- 15 - Voltage signal V_{ph}
- digital voltage values V_{bi}
- substrate 25
- first ohmic contact BC
- second ohmic contact TC
- 20 - first face 30
- first doped region 31
- second face 32
- second doped region 33
- layer in a second semiconductor material 34
- 25 - third face 35

- doped layer 36
- first metallic layer 37
- second metallic layer 38
- first high doping pocket 39
- 5 - second high doping pouch 40
- third metal layer 41
- fourth metal layer 42
- fifth metal layer 43
- insulating layer 44
- 10 - free face 45
- first contact pad 46
- second contact pad 47
- third ohmic contact FC
- third high doping pocket 48
- 15