

PHOTODETECTOR COMPRISING A PHOTONIC CRYSTAL STRUCTURE OPTICALLY COUPLED TO AN ACTIVE LAYER HAVING AN IMPROVED QUANTUM EFFICIENCY

TECHNICAL FIELD

The field of the invention is that of photodetectors, for example array photodetectors, comprising a grating structure and an active layer adapted to absorbing the light radiation to
5 be detected.

PRIOR ART

Photodetectors of an electromagnetic radiation are adapted to receiving and detecting the electromagnetic radiation by converting it into an output luminous or electrical signal, such
10 as, for example, an output signal formed of charge carriers photogenerated in an active layer.

Document WO2014/056550 describes an example of an electronic radiation photodetector, such as an image intensifier tube or a photomultiplier tube. As illustrated in Figure 1, photodetector A1 comprises an inlet window A10 transparent to the radiation to be detected, and an active photoemissive layer A30 arranged on a back side of inlet window A10. The
15 latter is adapted to receiving the incident electromagnetic radiation and to transmitting as a response a photoelectron flux. An output device (not shown) receives the photoelectrons and generates as a response an output signal, here after having multiplied the photoelectrons into a secondary electron flux.

The quantum efficiency of active layer A30 corresponds to the ratio of the number of emitted
20 photoelectrons to the number of received incident photons. It depends in particular on the incident photon absorption rate, on the photoelectron transport rate to the emission surface (back side of the active layer), and on the photoelectron emission rate outside active layer A30.

Since the absorption and transport rates depend on the thickness of active layer A30
25 according to opposite tendencies, that is, the absorption rate increases with the thickness while the transport rate decreases, there thus exists an optimal thickness enabling to maximize the product of these two rates. However, there appears that the absorption rate strongly decreases for high wavelengths, here, in particular from approximately 800 nm. To

improve the performance of photodetector A1, a natural solution then would be to increase the thickness of active layer A30 to increase the absorption rate, but, as it has been seen, this would result in a degradation of the transport rate.

Also, photodetector A1 comprises a grating structure A20 forming a transmission diffraction grating, located between inlet window A10 and active layer A30. Also, an incident photon transmitted by this diffraction grating penetrates into active layer A30 with a non-zero diffraction angle relative to the normal to the front side of active layer A30. The apparent thickness of active layer A30, seen by the photon, is thus higher, which improves the absorption rate without for the transmission rate to be degraded. Thus, the quantum efficiency of active layer A30 is improved.

However, there exists a need to improve the performance of such a photodetector, and more widely of any photodetector formed of a transparent support layer, of a grating structure, and of an absorbing active layer.

15 DISCUSSION OF THE INVENTION

For this purpose, the object of the invention is a photodetector comprising a transparent support layer, a grating structure (photonic crystal structure), and an absorbing active layer, this photodetector having an improved performance, particularly due to an increase in the quantum efficiency of the active layer.

20 For this purpose, the object of the invention is a photodetector adapted to detecting a light radiation in a predefined detection spectral band, comprising a stack formed of:

- a support layer, made of a transparent material, adapted to receiving the light radiation from a front side, and to transmitting it through a back side;
- a grating structure, arranged on the back side of the support layer, comprising patterns arranged in a main plane parallel to the front side of the support layer;
- an active layer, arranged on a back side of the grating structure, made of a semiconductor material adapted to absorbing light radiation.

According to the invention, the grating structure comprises a structured layer, which is formed of said patterns and of a continuous sub-layer of non-zero constant thickness e_{ccs} , the patterns facing the support layer and having a profile widening along a direction towards the continuous sub-layer.

Further, the grating structure, referred to as photonic crystal structure, has dimensions such that the structured layer forms a photonic crystal which supports at least one guided mode capable of being excited by the incident light radiation of interest, the photonic crystal being optically coupled to the active layer so that the guided mode is optically confined in the structured layer and the active layer.

Certain preferred but non-limiting aspects of this photodetector are the following.

The patterns may have a height h , between their top and their base, in the range from one tenth to three quarters of the thickness e_{ccs} of the continuous sub-layer of the structured layer.

The photonic crystal structure may comprise a so-called filling layer, located between the support layer and the structured layer, made of a dielectric material having a refraction index n_L smaller than a refraction index n_H of the structured layer and exhibiting a difference $n_H - n_L$ at least equal to 0.2.

The refraction index n_L of the filling layer may exhibit a difference in absolute value $|n_L - n_{cs}|$ with a refraction index of the support layer at most equal to 0.1.

A refraction index n_H of the structured layer may exhibit a difference in absolute value $|n_H - n_{ca}|$ with a refraction index of the active layer at most equal to 0.5.

The sum of a height h of the patterns, of a thickness e_{ccs} of the continuous sub-layer of the structured layer, and of a thickness e_{ca} of the active layer, may be at least equal to $\lambda_r / (2 \times \langle n'_H \rangle)$, where λ_r is a wavelength of the guided mode, and where $\langle n'_H \rangle$ is an average index equal to an average of the refraction indices of the structured layer and of the active layer weighted by the respective thicknesses.

The patterns may have a parabolic profile.

The active layer may have a back side opposite to the photonic crystal structure (20), in contact with vacuum.

The filling layer may be made of an oxide, or even of a silicon oxide.

The active layer may be a photoemissive layer made of a material based on SbNaKCs, SbNa₂KCs, SbNaK, SbKCs, SbRbKCs, or SbRbCs, or of a material based on AgOCs.

The photodetector may be an image intensifier tube or a photomultiplier tube.

The invention also relates to a method of manufacturing a photodetector according to any of the foregoing characteristics, comprising the following steps:

- forming of a stack formed of a thick layer, of a so-called filling layer, and of an upper thin film;
- forming of through openings in the upper thin film and emerging onto the filling layer, regularly arranged at pitch p of the patterns;
- 5 ○ partial isotropic wet etching of the filling layer from the through openings, to form periodic etched areas intended to form the patterns; and then removal of the upper thin film;
- deposition on the filling layer of a layer forming the structured layer;
- deposition on the structured layer of the active layer;
- 10 ○ removal of the thick layer, and assembly of the support layer to the exposed surface of the filling layer.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, objects, advantages and features of the invention will become apparent on
 15 reading of the following detailed description of preferred embodiments thereof, provided as a non-limiting example, and in relation with the accompanying drawings, in which:

Figure 1, already described, is a simplified and partial view, in transverse cross-section, of a photodetector according to an example of prior art;

Figure 2A is a simplified and partial view, in transverse cross-section, of a photodetector
 20 according to an embodiment;

Figure 2B illustrates in further detail the photonic crystal structure of the photodetector of Figure 2A;

Figure 2C is a top view of the structured layer of the photodetector of Figure 2A;

Figure 3A illustrates examples of absorption and reflection spectrums of a photodetector
 25 similar to that of Figure 2A;

Figure 3B illustrates examples of absorption and reflection spectrums of a photodetector according to a variant of that of Figure 2A;

Figure 3C illustrates an example of spectral power density of a light radiation in night vision;

Figures 4A to 4F illustrate steps of a method of manufacturing a photodetector similar to
 30 that of Figure 2A.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

In the drawings and in the following description, same references represent identical or similar elements. Further, the different elements are not shown to scale, to privilege the readability of the drawings. Further, the different embodiments and variants are not
 5 exclusive of one another and may be combined. Unless specified otherwise, the terms "substantially", "approximately", "in the order of" signify to within 10%, and preferably to within 5%. Further, the terms "in the range from ... to ..." and the like signify that the limits are included, unless specified otherwise.

- 10 The invention relates to a photodetector adapted to detecting a light radiation in a predefined detection spectral band $\Delta\lambda_{\text{det}}$. It comprises a stack formed of, along a main direction, a transparent support layer, a grating structure (referred to hereafter as 'photonic crystal structure'), and an active layer adapted to absorbing the incident light radiation.

The main direction is a direction parallel or inclined with respect to the normal to the front
 15 side of the transparent support layer through which the light radiation to be detected enters into the photodetector. It also defines the optical axis of the photodetector along which the incident light radiation propagates. A main plane can be defined as being a plane parallel to the front side of the transparent support layer. In the following description, the main direction is parallel to the main plane, but an inclination by a few degrees, preferably at most 10°,
 20 remains possible.

As detailed hereafter, the photodetector performance is improved by the fact that the photonic crystal structure has dimensions such that the structured layer forms a photonic crystal which supports at least one guided mode capable of being excited by the incident light radiation of interest, which extends in the plane of the photonic crystal. Further, the
 25 photonic crystal is optically coupled to the active layer, so that the guided mode is optically confined in the photonic crystal and the active layer.

For this purpose, the guided mode is excited in normal incidence or inclined (along the optical axis) by a so-called guided mode resonance (GMR) effect, at a high predetermined wavelength of detection spectral band $\Delta\lambda_{\text{det}}$, referred to as resonance wavelength λ_r , where
 30 the absorption rate of the active layer is usually relatively low in the absence of such a photonic crystal structure. The absorption rate is thus particularly high at this resonance wavelength λ_r , while the transport rate remains unchanged.

The photonic crystal is formed by the patterns of a structured layer made of a dielectric of high refraction index n_H . These patterns are preferably arranged periodically, but a quasi-periodic, or even non-periodic, arrangement such as for example correlated disorder, is also possible. The photonic crystal gives birth to band gaps for light propagation along certain directions and at certain wavelengths, similarly to electronic band gaps in semiconductors. The photonic crystal is here preferably two-dimensional, in that the patterns are arranged along two distinct axes of the main plane in which the structured layer extends. Further, as subsequently described, it is possible to slow down the light in the photonic crystal, and it is laterally confined in the plane of the structured layer.

As detailed hereafter, the photodetector performance is improved by the fact that the reflection rate, defined at the interface between the support layer and the photonic crystal structure, is decreased. This is obtained by the fact that the patterns of the photonic crystal, which extend vertically from a continuous sub-layer of constant thickness towards the support layer, have a profile which widens along the main direction, so that the fill factor associated with the patterns increases along the main direction from a zero value to at least 80%, or even at least 90% or more. By this profile of the patterns, which is preferably parabolic, the refraction index, associated with the patterns (and thus with their fill factor) (explained hereafter), has a value which increases along the main direction, passing from a low value n_L substantially equal to the refraction index of a filling layer and of the support layer, to a high value substantially equal, to at least 10%, to the high index n_H of the material of the structured layer of the grating structure. There appears that this decrease of the reflection rate is wideband, which improves the photodetector performance.

Figure 2A is a transverse cross-section view, simplified and partial, of a photodetector 1 according to an embodiment. Figure 2B illustrates a portion of photonic crystal structure 20, and Figure 2C is a top view of the structured layer 22 of photonic crystal structure 20.

In this example, photodetector 1 is an image intensifier tube (for example of EB-CCD or EBCMOS type) or a photomultiplier tube, and active layer 30 is a semitransparent photocathode. The light radiation to be detected has a spectral range which spans detection spectral band $\Delta\lambda_{\text{det}}$, which here approximately ranges from 0.5 μm to 1 μm .

According to the invention, photodetector 1 comprises *a minima* a stack formed, along the main direction, of a transparent support layer 10, of a photonic crystal structure 20, and of

an active layer 30. An output device (not shown) is located downstream of active layer 30, and is adapted to receiving the charge carriers photogenerated in active layer 30 to generate in response an output optical or electrical signal.

In the case, here, where photodetector 1 is an image intensifier tube or a photomultiplier tube, the output device may then comprise a photoelectron multiplier device (for example a microchannel wafer) followed by a phosphor screen and/or, if relevant, by a CMOS or CCD array sensor. However, the invention is not limited to this type of photodetectors nor to photocathodes.

There is here defined, and for the rest of the disclosure, direct three-dimensional orthogonal reference frame XYZ, where axes X and Y form a main plane along which the layers extend, and where axis Z is oriented along the thickness of the layers. Direction +Z is oriented from support layer 10 towards active layer 30. It forms the main direction along which the light radiation to be detected enters into the photodetector (the main direction may however be inclined relative to the normal to main plane XY, preferably by approximately at most 10°). Further, the terms "front" and "back" should be understood as being relative to an increasing positioning along main direction +Z.

Support layer 10 forms an inlet window for the light radiation to be detected in photodetector 1. It has a front side 10av through which the light radiation is received, and a back side 10ar, opposite to front side 10av, through which the received light radiation is transmitted towards photonic crystal structure 20. Front and back sides 10av and 10ar are here substantially parallel to main plane XY.

Support layer 10 is made of a material transparent in detection spectral band $\Delta\lambda_{\text{det}}$, that is, its transmittance (transmission rate) is very high, for example close to 100%. It is made of a material selected according to the spectral range of the light radiation to be detected. In detection spectral band $\Delta\lambda_{\text{det}}$ approximately ranging from 0.5 to 1 μm , the material may be, for example, quartz or borosilicate glass.

Support layer 10 may have a thickness in the range from a few hundreds of microns to a few millimeters. As an example, support layer 10 is made of quartz, and has a thickness of approximately 2 mm. It has a refraction index noted n_{cs} .

Photonic crystal structure 20 is arranged on the back side 10ar of support layer 10. It comprises patterns 22.1 arranged in main plane XY, here periodically. It is sized to form a photonic crystal enabling to improve the absorption in active layer 30, and patterns 22.1 have

a profile which widens from the top to the base to decrease the reflection rate at the interface between support layer 10 and photonic crystal structure 20.

Photonic crystal structure 20 comprises a first layer 21, referred to as filling layer, made of a dielectric material, transparent in detection spectral band $\Delta\lambda_{\text{det}}$, and having a low refraction index n_L . It here extends in main plane XY in contact with support layer 10, but an intercalary layer (not shown), also made of a transparent material of low refraction index, may be located between and in contact with support layer 10 and filling layer 21.

Refraction index n_L exhibits a difference in absolute value $|n_L - n_{\text{cs}}|$ with the refraction index n_{cs} of support layer 10 preferably smaller than or equal to 0.1, defined at resonance wavelength λ_r of the guided mode supported by the photonic crystal, comprised in detection spectral band $\Delta\lambda_{\text{det}}$, to limit the reflection of the light radiation at the interface between support layer 10 and filling layer 21. Preferably, refraction index n_L is substantially equal to that of support layer 10. As an example, the filling layer is made of a silicon oxide, for example of SiO_2 , having its refraction index n_L varying from 1.4623 to 1.4504 in spectral band $\Delta\lambda_{\text{det}} = [0.5; 1 \mu\text{m}]$.

Filling layer 21 here comprises a continuous sub-layer 21.1 of constant thickness e_{ccr} , here non-zero but which may be zero, from which there extend along main direction +Z portions 21.2 which fill the space located between the patterns 22.1 of photonic crystal structure 20. Thickness e_{ccr} is here defined along axis Z between the front side 20av of photonic crystal structure 20 and a plane running through the top of patterns 22.1. As an example, in the case of $\Delta\lambda_{\text{det}} = [0.5; 1 \mu\text{m}]$, thickness e_{ccr} may be in the order of approximately $0.5 \mu\text{m}$. As described hereafter, this value may be optimized to improve the absorption rate in active layer 30 by guided mode resonance effect, and to decrease the reflection rate at the interface between support layer 10 and photonic crystal structure 20.

Photonic crystal structure 20 also comprises a second layer 22, referred to as structured layer, made of a dielectric material, transparent in detection spectral band $\Delta\lambda_{\text{det}}$, and having a high refraction index n_H greater than n_L . It extends in main plane XY, and is formed of patterns 22.1 and of a continuous sub-layer 22.2 of non-zero constant thickness e_{ccs} , from which patterns 22.1 extend towards support layer 10.

Refraction index n_H exhibits a difference $n_H - n_L$ with respect to index n_L of filling layer 21 preferably greater than or equal to 0.2 at resonance wavelength λ_r , to ensure an optical confinement of the guided mode in the photonic crystal. As an example, structured layer 22

is made of a titanium oxide, for example of TiO_2 , having its refraction index n_H varying from 2.7114 to 2.4856 in spectral band $\Delta\lambda_{\text{det}} = [0.5; 1 \mu\text{m}]$, so that difference $n_H - n_L$ varies between 1.2491 and 1.0352. This difference is 1.0794 at the 0.75- μm resonance wavelength λ_r . Further, index n_H has a difference in absolute value $|n_H - n_{\text{ca}}|$ with respect to the refraction index n_{ca} of active layer 30 smaller than or equal to 0.5, and is preferably substantially equal thereto, so that the guided mode supported in structured layer 22 (the photonic crystal) sufficiently covers active layer 30 (it is then spoken of a supermode).

Preferably, the sum of the thicknesses of the high-index mediums, that is, the height h of patterns 22.1, the thickness e_{ccs} of continuous sub-layer 22.2, and the thickness e_{ca} of active layer 30 is such that: $h + e_{\text{ccs}} + e_{\text{ca}}$ is at least equal to $\lambda_r/2\langle n'_H \rangle$, and preferably at least equal to $\lambda_r/\langle n'_H \rangle$, or even at least equal to $3\lambda_r/2\langle n'_H \rangle$. Thus, the conditions for structured layer 22 and active layer 30 to support at least one supermode are improved. Refraction index $\langle n'_H \rangle$ here is an average of the index n_H of structured layer 22 and of the index n_{ca} of active layer 30, weighted by the respective thicknesses ($h + e_{\text{ccs}}$ for structured layer 22; e_{ca} for active layer 30), or, more precisely, an average of the permittivities of layers 22 and 30 weighted by the respective volume fractions (according to the effective medium Bruggeman model).

Continuous sub-layer 22.2 has a thickness e_{ccs} defined along axis Z between a plane running through the base of patterns 22.1 and the back side 20ar of photonic crystal structure 20. As an example, in the case of $\Delta\lambda_{\text{det}} = [0.5; 1 \mu\text{m}]$, thickness e_{ccs} may be in the order of approximately 0.35 μm . As described hereafter, this value may be optimized to minimize the reflection rate in detection spectral band $\Delta\lambda_{\text{det}}$ and maximize the absorption rate at resonance wavelength λ_r .

Patterns 22.1 extend from continuous sub-layer 22.2 towards support layer 10. They have a height h along axis Z , defined between a plane running through their top and a plane running through their base (at the interface with sub-layer 22.2). They are regularly arranged in plane XY with a pitch p (constant if the arrangement is periodic). The arrangement of patterns 22.1 is preferably two-dimensional, in that it extends along two distinct axes in plane XY , as illustrated in Figure 2C. It enables to make photodetector 1 insensitive to the polarization of the incident light radiation. Further, a two-dimensional photonic crystal is likely to support a plurality of guided modes at different resonance wavelengths (a plurality of resonances in spectral band $\Delta\lambda_{\text{det}}$). In such a case, resonance wavelength λ_r , which the most efficiently improves the absorption at the edge of the bandgap of active layer 30, is essentially considered.

Height h is preferably in the range from $e_{\text{ccs}}/10$ to $3e_{\text{ccs}}/4$ so that the resonance has a significant effect on the absorption rate. Further, it is defined while taking into account thicknesses e_{ccs} and e_{ca} , and refraction indices n_{H} and n_{ca} so that the supermode is supported and correctly spreads in active layer 30. As an example, height h may be equal to approximately $0.35 \mu\text{m}$, and is a value to be optimized to minimize the reflection rate in detection spectral band $\Delta\lambda_{\text{det}}$ and maximize the absorption rate at resonance wavelength λ_r .

Further, patterns 22.1 have a profile having a width l_{H} increasing along main direction $+Z$. The profile is defined as the envelope of a transverse cross-section of patterns 22.1 along a plane running through the top of the pattern and parallel to axis Z . In other words, the width l_{H} of patterns 22.1 increases from the top to the base of patterns 22.1. Patterns 22.1 may have the shape of a cone, having its top truncated or not, and its base circular, oval, polygonal, etc. The profile of patterns 22.1 may be triangular or curved, preferably parabolic. Also, this enables to decrease the reflection rate at the interface between support layer 10 and photonic crystal structure 20, over the entire detection spectral band $\Delta\lambda_{\text{det}}$.

Thus, when an elementary volume V_{elem} of photonic crystal structure 20 is considered in a plane XY , which runs through the center of patterns 22.1 as illustrated in Figures 2B and 2C, an average refraction index can be defined as being the average of refraction index n_{L} and of refraction index n_{H} as a function of the fill factor ff of the patterns 22.1 present in elementary volume V_{elem} . In other words : $\langle n(z) \rangle = n_{\text{H}} \times \text{ff}(z) + n_{\text{L}} \times (1 - \text{ff}(z))$. Fill factor $\text{ff}(z)$ varies along main direction $+Z$ as being the ratio of the surface area $s_{\text{H}}(z)$ of the patterns in plane XY at ordinate z to the total surface area $S_{\text{elem,tot}}$ of elementary volume V_{elem} . The value of the average refraction index increases along direction $+Z$, from the low value n_{L} at the top of patterns 22.1 to a high value close to n_{H} at the base of patterns 22.1, or preferably at least equal to 90% of n_{H} .

Preferably, the profile of patterns 22.1 is parabolic so that the average refraction index $\langle n(z) \rangle$ linearly increases. Indeed, there appears that a parabolic profile ensures an optimal decrease of the reflection rate in detection spectral band $\Delta\lambda_{\text{det}}$.

Further, as previously indicated, arrangement pitch p and height h are selected, as well as the thickness e_{ccs} of continuous sub-layer 22.2, and preferably also the thickness e_{ccr} of continuous sub-layer 21.1, so that structured layer 22 forms a photonic crystal which supports at least one guided mode capable of being excited by the incident light radiation of interest. Further, the photonic crystal is optically coupled to active layer 30, so that the guided mode is optically confined in the photonic crystal and active layer 30.

More specifically, the light radiation incident on photonic crystal structure 20 excites one or a plurality of modes supported by the photonic crystal, by a guided mode resonance (GMR) effect. A description of this guided mode resonance effect can in particular be found in the article of Magnusson & Ko entitled *Guided-mode resonance nanophotonics: Fundamentals and applications*, SPIE 9927, Nanoengineering: Fabrication, Properties, Optics, and Devices XIII, 992702 (15 September 2016). Also, a guided mode, of predefined wavelength λ_r , is present in the waveguide formed by structured layer 22 and is oriented in plane XY. Resonance wavelength λ_r is of course comprised in detection spectral band $\Delta\lambda_{\text{det}}$, and is located at high wavelengths, for example around approximately 850 nm or 900 nm, where the absorption rate of active layer 30 normally drops, that is, in the absence of the photonic crystal structure 20 according to the invention.

For this purpose, the thickness e_{ccs} of continuous sub-layer 22.2 is selected so that the resonant guided mode transversely spreads on active layer 30 (supermode), so that the absorption rate of active layer 30 is then improved at resonance wavelength λ_r , without for the transport rate to be degraded (due to an increase in the thickness of active layer 30).

Further, arrangement pitch p is selected so that propagation constant of the guided mode of the n th diffraction order, defined as $\beta_n = n \times 2\pi/p$, is in the range from refraction index n_L to the minimum value among refraction index n_H and that of active layer 30. Further, height h , as well as arrangement pitch p , are selected to obtain this guided mode resonance effect. When this guided mode resonance effect is obtained, the resonant guided mode satisfies a Bloch condition, so that its groups velocity $\partial\omega/\partial k$ is substantially zero (ω is the pulse and k is the wave vector). Also, the resonant guided mode forms a stationary wave, and may be designated as a "slow Bloch mode". Also, the resonant guided mode remains located, in plane XY, at the location where it has been excited by the incident light radiation. It is then absorbed in active layer 30 in this same area in plane XY, which improves the contrast of photodetector 1, or even enables to limit *crosstalk* or halo effects in the case of an array photodetector 1. As an example, pitch p may be equal to approximately 0.55 μm , and is also a value to be optimized to minimize the reflection rate in detection spectral band $\Delta\lambda_{\text{det}}$ and to maximize the absorption rate at resonance wavelength λ_r .

Active layer 30 rests on the back side 20ar of photonic crystal structure 20. It is adapted to absorbing the light radiation of interest in detection spectral band $\Delta\lambda_{\text{det}}$. It is made of a semiconductor material adapted to absorbing the light radiation of interest, having its resonant guided mode oriented in plane XY and optically confined in structured layer 22

(photonic crystal) and in active layer 30. It has a thickness e_{ca} substantially constant in plane XY.

In the case of a photocathode, it may be, for example, a crystalline material based on antimony and alkaline metal, or based on silver oxide, for example a material selected from
 5 among $SbNaKC$ s, $SbNa_2KC$ s, $SbNaK$, $SbKC$ s, $SbRbKC$ s, or $SbRbC$ s. The material of the photocathode may also be formed based on $AgOC$ s. As previously indicated, the semiconductor material has a refraction index n_{ca} substantially equal to that of the material of the structured layer, or exhibiting a difference in absolute value $|n_{ca}-n_H|$ at most equal to 0.5. It has a thickness preferably smaller than or equal to 300 nm, for example equal to
 10 approximately 140 nm.

Thus, photodetector 1 has a performance improved due to photonic crystal structure 20, which ensures, on the one hand a wideband decrease of the reflection at the interface between support layer 10 and photonic crystal structure 20, and on the other hand a resonant excitation of at least one guided mode supported in structured layer 22, which forms a photonic crystal,
 15 this resonant guided mode also being optically confined in the active layer.

Photodetector 1 may be in array form, and may comprise a CMOS array sensor (not shown), located downstream of the active layer, and more specifically downstream of a phosphor screen. Thus, the back side of the active layer may be in contact with vacuum, and a multiplier device may be located between the active layer, to multiply the photoelectrons
 20 into a high flux of secondary electrons oriented towards the phosphor screen. The photons generated by the phosphor screen are then detected by the CMOS array sensor. Preferably, each detection pixel of the CMOS sensor has a dimension, in plane XY, equal to an integer number of periods p .

It should here be noted that an approach to determine the values of pitch p , of height h , and
 25 of thicknesses e_{ccr} and e_{ccs} , to form the photonic crystal and the guided mode resonance, may consist of solving the Maxwell equations by a method of rigorous coupled-wave analysis (RCWA), by performing a parametric study.

Thus, each of parameters p , h , e_{ccr} , and e_{ccs} varies over a predefined range, and the spectral response of the photodetector in absorption $A(\lambda)$ and in reflection $R(\lambda)$ is calculated. The
 30 presence of an absorption peak at the resonance wavelength λ_r can thus be verified. Then, to obtain the optimal values, two figures of merit can be calculated, that is, one figure of merit FOM_A associated with the absorption spectrum, which is defined as being the integral over

the detection spectral band of a correlation of the absorption spectrum $A(\lambda)$ with a predefined intensity spectrum $NV(\lambda)$ (spectral power density of a light radiation in night vision). Similarly, a figure of merit FOM_R associated with the reflection spectrum is defined as being the integral of the correlation of the reflection spectrum $R(\lambda)$ with the intensity spectrum $NV(\lambda)$. The two figures of merit can thus be written as:

$$FOM_A = \int_{0.5\mu m}^{1\mu m} (A \cdot NV) d\lambda; FOM_R = \int_{0.5\mu m}^{1\mu m} (R \cdot NV) d\lambda$$

The optimal values which maximize absorption rate A at the resonance wavelength while minimizing reflection rate R over the detection spectral band can thus be selected based on one and/or the other of the figures of merit.

In this regard, Figures 3A and 3B illustrate examples of the absorption and reflection spectrums $A(\lambda)$ and $R(\lambda)$ of the photodetector, for two examples of sizing of the photonic crystal structure. These spectrums are obtained by numerical solving of Maxwell's equations, here by an RCWA technique. The detection spectral band here extends from 0.5 to 1 μm . Further, Figure 3C illustrates an example of a spectral power density of a light radiation in night vision.

In these examples, photodetector 1 is formed of a transparent silicon oxide support layer 10, of a photonic crystal structure 20 formed of a first filling layer 21 made of SiO_2 and of a second structured layer 22 made of TiO_2 , and then of a thin film of Al_2O_3 , and finally of an active layer 30 such as a photocathode formed based on antimony and on at least one alkaline metal (of type S25).

Filling layer 21 comprises a continuous sub-layer 21.1 of constant thickness e_{ccr} , and structured layer 22 comprises a continuous sub-layer 22.2 of constant thickness e_{ccs} and patterns 22.1 regularly arranged along two distinct axes contained in plane XY. Patterns 22.1 have a height h , a pitch p , and a maximum fill factor ff_{max} defined at the base of patterns 22.1. Patterns 22.1 have a parabolic shape with a circular base, so that fill factor ff , and thus the average refraction index, varies linearly along direction +Z.

The parametric study is performed by here varying parameters p , h , e_{ccr} , and e_{ccs} over the following ranges: for p , from 0.5 to 0.63 μm , for h from 0.25 to 0.55 μm , for e_{ccr} from 0.23 to 0.55 μm , and for e_{ccs} from 0.23 to 0.45 μm .

Figure 3A illustrates the absorption and reflection spectrums $A(\lambda)$ and $R(\lambda)$, in the case where photonic crystal structure 20 has been sized to maximize figure of merit FOM_A . In

this case, pitch p is equal to $0.6\ \mu\text{m}$, height h is equal to $0.39\ \mu\text{m}$, the thickness e_{b1} of the upstream region is equal to $0.49\ \mu\text{m}$, and the thickness e_{b2} of the downstream region is equal to $0.29\ \mu\text{m}$. There appears that figure of merit FOM_A is equal to 8.9966 over the $0.5\text{-}1\ \mu\text{m}$ detection spectral band. This high value is due to the fact that the absorption spectrum exhibits an absorption peak around $875\ \text{nm}$, representative of the presence of a guided mode resonance in the photonic crystal and thus in the active layer. Further, the reflection is particularly low over the entire detection spectral band, with a figure of merit FOM_R equal to 1.8846.

Figure 3B illustrates the absorption and reflection spectrums $A(\lambda)$ and $R(\lambda)$, in the case where photonic crystal structure 20 has been sized to maximize figure of merit FOM_B . In this case, pitch p is equal to $0.53\ \mu\text{m}$, height h is equal to $0.33\ \mu\text{m}$, the thickness e_{b1} of the upstream region is equal to $0.55\ \mu\text{m}$, and the thickness e_{b2} of the downstream region is equal to $0.35\ \mu\text{m}$. There appears that figure of merit FOM_A remains high, with a 7.4456 value, due to the presence of an absorption peak around $850\ \text{nm}$ linked to a guided mode resonance in the photonic crystal and thus in the active layer. Further, the reflection is further decreased, with a figure of merit FOM_R equal to 1.2261.

Also, photodetector 1 has a particularly high quantum efficiency, due to the fact that photonic crystal structure 20 enables both to optimize the absorption rate in the active layer, particularly at the resonance wavelength, and to decreases the reflection rate over the detection spectral band, without for all this degrading the transport rate.

Figures 4A to 4F illustrate steps of a method of manufacturing a photodetector 1 identical or similar to that of Figure 2A.

Referring to Figure 4A, there is first provided a stack formed, from bottom to top, of a thick silicon layer 40 (for example a silicon wafer having a thickness of several hundred microns), of a buried oxide layer 21 having a thickness of approximately $2\ \mu\text{m}$, of a thin film 41 of amorphous silicon having a 100-nm thickness, and of a thin film 42 of silicon oxide having a thickness of approximately $100\ \text{nm}$. The buried oxide is preferably formed by oxidation of the silicon of the thick layer.

Referring to Figure 4B, there are formed periodic openings 43 through thin oxide film 42 and thin silicon film 41, which emerge onto the upper surface of buried oxide layer 21. Openings 43 are formed at the pitch p desired for the structured layer. For this purpose, a

hard mask is deposited on thin oxide film 42, which is structured to form through openings. Then, openings 43 are formed through thin oxide film 42 by dry RIE-type etching. Then, the openings are formed through thin silicon film 41 by dry RIE-type etching.

Referring to Figure 4C, thin oxide film 42 is removed, for example by dry RIE etching. The
 5 upper surface of thin silicon film 41 is then exposed.

Referring to Figure 4D, there is performed a partial etching of buried oxide layer 21 from the periodic openings present in thin silicon film 41, to form etched areas 44 having a desired periodic profile. The etching here is an isotropic wet etching, for example of BOE (oxide
buffered oxide etch) type. The etch depth corresponds to the desired height h of the patterns
 10 of the photonic crystal structure. The ratio of the vertical etch speed to the horizontal etch speed enables to control the profile of etched areas 44. There can be defined in buried oxide layer 21 a continuous lower portion of constant thickness e_{ccr} .

Referring to Figure 4E, the structured thin silicon film 41 is removed, to provide access to the upper surface of buried oxide layer 21. A layer 22 of a material of high refraction index,
 15 for example here made of TiO_2 , is doped to fill etched areas 44, which forms the patterns, and to form a continuous sub-layer of constant thickness e_{ccs} , and the upper surface of layer 22 of high index is planarized, for example by a chemical-mechanical planarization. An intermediate thin film 45 (optional), for example made of Al_2O_3 may be deposited. Then, active layer 30 is deposited to cover high-index layer 22.

20 Referring to Figure 4F, the obtained stack is flipped, after which thick silicon layer 40 is removed, and a support layer 10 made of quartz or of borosilicate glass is bonded to the exposed surface of buried oxide layer 21.

Thus, a photodetector 1 identical or similar to that illustrated in Figure 2A is obtained, which comprises transparent support layer 10, photonic crystal structure 20, and active layer 30.

25 Specific embodiments have just been described. Different variants and modifications will occur to those skilled in the art.

CLAIMS

1. Photodetector (1) adapted to detecting a light radiation in a predefined detection spectral band, comprising a stack formed of:
 - 5 ○ a support layer (10), made of a transparent material, adapted to receiving the light radiation from a front side (10av) and to transmitting it through a back side (10ar);
 - a grating structure (20), arranged on the back side (10ar) of the support layer (10), comprising patterns (22.1) arranged in a main plane parallel to the front side (10av) of the support layer (10);
 - 10 ○ an active layer (30), arranged on a back side (20ar) of the grating structure (20), made of a semiconductor material adapted to absorbing the light radiation; characterized in that:
 - the grating structure (20) comprises a structured layer (22), which is formed of said patterns (22.1) and of a continuous sub-layer (22.2) of non-zero constant
 15 thickness e_{ccs} , the patterns (22.1) facing the support layer (10) and having a profile widening along a direction towards the continuous sub-layer (22.2);
 - the grating structure (20), referred to as photonic crystal structure, has dimensions such that the structured layer (22) forms a photonic crystal which supports at least one guided mode capable of being excited by the incident light radiation of
 20 interest, the photonic crystal being optically coupled to the active layer (30) so that the guided mode is optically confined in the structured layer (22) and the active layer (30).
2. Photodetector (1) according to claim 1, wherein the patterns (22.1) have a height h , between their top and their base, in the range from one tenth to three quarters of the
 25 thickness e_{ccs} of the continuous sub-layer (22.2) of the structured layer (22).
3. Photodetector (1) according to claim 1 or 2, wherein the photonic crystal structure (20) comprises a so-called filling layer (21), located between the support layer (10) and the structured layer (22), made of a dielectric material having a refraction index n_L smaller than a refraction index n_H of the structured layer (22) and exhibiting a difference $n_H - n_L$ at least equal to 0.2.
 30

4. Photodetector (1) according to claim 3, wherein the refraction index n_L of the filling layer (21) exhibits a difference in absolute value $|n_L - n_{cs}|$ with a refraction index of the support layer (10) at most equal to 0.1.
5. Photodetector (1) according to any of claims 1 to 4, wherein a refraction index n_H of the structured layer (22) exhibits a difference in absolute value $|n_H - n_{ca}|$ with a refraction index of the active layer (30) at most equal to 0.5.
6. Photodetector (1) according to any of claims 1 to 5, wherein the sum of a height h of the patterns (22.1), of a thickness e_{ccs} of the continuous sub-layer (22.2) of the structured layer (22), and of a thickness e_{ca} of the active layer (30) is at least equal to $\lambda_r / (2 \times \langle n'_H \rangle)$, where λ_r is a wavelength of the guided mode, and where $\langle n'_H \rangle$ is an average index equal to an average of the refraction indices of the structured layer (22) and of the active layer (30) weighted by the respective thicknesses.
7. Photodetector (1) according to any of claims 1 to 6, wherein the patterns (22.1) have a parabolic profile.
8. Photodetector (1) according to any of claims 1 to 7, wherein the active layer (30) has a back side opposite to the photonic crystal structure (20), in contact with vacuum.
9. Photodetector (1) according to any of claims 1 to 8 and of claim 3, wherein the filling layer (21) is made of an oxide.
10. Photodetector (1) according to claim 9, wherein the filling layer (21) is made of a silicon oxide.
11. Photodetector (1) according to any of claims 1 to 10, wherein the active layer (30) is a photoemissive layer made of a material based on SbNaKCs, SbNa₂KCs, SbNaK, SbKCs, SbRbKCs, or SbRbCs, or of a material based on AgOCs.
12. Photodetector (1) according to any of claims 1 to 11, the latter being an image intensifier tube or a photomultiplier tube.
13. Method of manufacturing a photodetector (1) according to any of the foregoing claims, comprising the following steps:

- forming of a stack formed of a thick layer (40), of a so-called filling layer (21), and of an upper thin film (41);
- forming of through openings (43) in the upper thin film (41) and emerging onto the filling layer (21), regularly arranged at pitch p of the patterns (22.1);
- 5 ○ partial isotropic wet etching of the filling layer (21) from the through openings (43), to form periodic etch areas (44) intended to form the patterns (22.1); and then removal of the upper thin film (41);
- deposition on the filling layer (21) of a layer (22) forming the structured layer;
- deposition on the structured layer (22) of the active layer (30);
- 10 ○ removal of the thick layer (40), and assembly of the support layer (10) on the exposed surface of the filling layer (21).