

INFRARED DETECTOR WITH NON-COOLED QUANTUM WELL
STRUCTURE

BACKGROUND OF THE INVENTION

The field of the invention is that of detectors
5 with quantum well structure working in the infrared
range, both in band II (between 3 and 5 μm) and in band
III (between 8 and 12 μm).

At present, there are three types of detectors used
in the infrared domain.

10 A first type relates to the detectors with Schottky
junction formed between silicon and platinum silicon
(Si/PtSi). These detectors perform well (as measured
by a minimum temperature detectable commonly called
NETD or noise equivalent temperature detectable of
15 about 80 mK in band II for reading frequencies of 50
Hz, surface areas of 50 μm x 50 μm and an optical
aperture of $f/2$), but have very low working
temperatures (of about 77 K).

A second type relates to bolometrical or
20 pyrometrical thermal detectors based on the changing of
electrical properties such as the dielectric index or
the resistance under the effect of heating due to the
radiation absorbed. These detectors lead to more
modest performances (with NETD values of about 120 mK
25 under the conditions of measurement described here
above and for band III). Nevertheless, their great
value is that they work at ambient temperature without
needing to be cooled.

A third type of detector relates to quantum
30 structure detectors using p-n junctions based on
semiconductors such as InSb, HgCdTe or PbSnSe or
intersubband transitions in quantum wells of materials
such as GaAs/AlGaAs.

These detectors have very high performance
35 characteristics (with NETD values in the neighborhood

of 20 mK) but work at temperatures in the range of 200 K in the best cases.

These last-mentioned detectors which perform very well therefore require cryogenic cooling. This represents an extra cost for the equipment.

Indeed, as described in R.J. Keyes, "Optical and Infrared Detectors", Springer-Verlag, the detectability of a component of this type is proportional to $I / \sqrt{I_{\text{dark}}}$ where I_{dark} is the dark current of the detector. In semiconductor-based quantum structure detectors, the current I_{dark} is thermally active, namely it varies as a function of the temperature in the form $I_{\text{dark}} \propto e^{-E_g/jkT}$

where E_g is the width of the gap of the semiconductor, close to the energy of the photon to be detected.

More specifically, the dark current in a photovoltaic detector is given by the following equation:

$$I_{\text{dark}} = I_{\text{diff}} + I_{\text{ZCE}}$$

with $I_{\text{diff}} = q L_{\text{diff}} n_i^2 / \tau_{\text{min}} \cdot N_{\text{dop}}$
 and $I_{\text{ZCE}} = q n_i d / \tau_{\text{min}}$
 where:

I_{diff} is the diffusion current
 I_{ZCE} is the space charge zone current
 L_{diff} is the diffusion length (typically some tens to some hundreds of microns)
 τ_{min} is the lifetime of the minority carriers
 n_i is the intrinsic carrier density
 d is the thickness of the space charge zone.

Figure 1 illustrates a standard photovoltaic detector having a p-n junction in which the lengths L_{diff} and d are shown.

In these detectors, it is particularly n_i^2 that gives the thermally activated term. Conventionally, by cooling these infrared detectors, the dark current and

therefore the associated noise are reduced. Furthermore, since the dark current is proportional to the thickness d of the detector zone, it is judicious to have a very thin detector zone. More specifically, the detectivity limited by the dark current is given by the formula:

$$D^* = \eta \lambda / [u^{1/2} h c \cdot (I_{\text{dark}} / q G^2 A)^{1/2}]$$

where

q is the charge of the electron

10 h is Planck's constant

c is the velocity of light

k is the Boltzmann constant

T is the temperature

G is the gain in photoconduction ($G = 1$ if the component is photovoltaic)

$u = 2$ if the component is photovoltaic

$u = 4$ if the component is photoconductive, and

η = the quantum yield given by the absorption of light in the layer with a thickness d giving:

$$20 \quad \alpha = 1 - e^{-\alpha d}$$

where α is the coefficient of absorption of the material.

The detectivity D^* is therefore proportional to:

$$D^* \propto \eta(d) / \sqrt{d}$$

25 and in the standard case $\eta(d) = 1 - e^{-\alpha d}$

Figure 2 illustrates the development of the detectivity D^* as a function of the thickness d . The curve 2a relates to standard quantum detectors in which $\eta(d) = 1 - e^{-\alpha d}$, these detectors typically using thicknesses in the range of one micron. The curve 2b pertains to a quantum detector in which $\eta(d)$ is constant. With this type of detector, it becomes particularly useful to work with a very low thickness d which may be in the range of $0.1 \mu\text{m}$ and a constant quantum yield η , the very low thickness d leading to

low dark currents that no longer require any device for the cooling of the detector.

SUMMARY OF THE INVENTION

To achieve the working conditions explained here
5 above, the detector with a quantum-well structure that
is an object of the invention is a detector comprising
a stack of layers of semiconductor materials on a
substrate with an electromagnetic wave detection zone,
wherein the stack of layers comprises a layer of
10 semiconductor material with low gap energy constituting
the detecting zone, contained between two layers of a
semiconductor material with high gap energy, and
wherein the detector comprises a coupling grating on
the stack of layers to obtain efficient coupling
15 between the optical wave to be detected and the
detector zone.

Advantageously, the layer of semiconductor material
with a small gap has a small thickness d , typically of
about 1000 Å to maintain low dark currents in the
20 detector.

The coupling grating for its part enables an
increase in the coupling between the detector zone and
the electromagnetic wave so as to keep a high quantum
yield η .

25 According to a first variant of the invention, the
quantum detector is a photoconductor detector
comprising electrical means to measure the variations
of resistivity due to the input of electrons into the
conduction band of the small-gap material, during the
30 detection of the optical wave. The region constituted
by semiconductor materials with a small gap having a
small thickness d is in this case inserted between two
layers constituted by large-gap semiconductor materials
SGC1 and SGC2 that are not doped and are therefore
35 ideally insulating at ambient temperature. A
diffracting grating may advantageously be etched on the

upper layer of semiconductor material SGC2. The pitch Λ of the grating is such that there is a resonance between the wavelength λ of the wave to be detected in the material (if n is the optical index of the material and the wavelength λ_0 of the electromagnetic wave to be detected, in a vacuum with $\lambda = \lambda_0/n$) and the grating, namely $\Lambda = \lambda_0/n$.

According to a second variant of the invention, the detector of the invention is a photovoltaic detector, the detector zone constituted by small gap semiconductor materials is inserted between two layers of large-gap semiconductor materials with p type and n type doping. In this case, the electron-hole pairs created by the absorption of the energy photons from the electromagnetic wave are separated by the electrical field that prevails in the p-n junction. The holes and/or the electrons may be drained towards the ends and develop a potential different proportional to the flux of photons detected, said potential difference being measured by electrical means located on either side of the stack of layers.

Advantageously, the detector of the invention may include two barrier layers of semiconductor materials with very large gaps STG_1 and STG_2 located at the interfaces of the layers of materials $SGG1/STG$ and $SGG2/SPG$ to prevent said interfaces from behaving like ohmic contacts.

Advantageously, the coupling network is etched in the layer of semiconductor material $SGG2$.

Advantageously, the detector according to the invention may include a layer of semiconductor material SG contained between the substrate and the stack of layers of semiconductor materials $SGG1/SPG/SGG2$, the material SG having a refraction index that is smaller than that of the substrate S to confine the wave in the stack of layers.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be understood more clearly and other advantages will appear from the following description, given on a non-restrictive basis with
5 reference to the appended drawings, of which:

- Figure 1 gives a schematic view of the lengths of detection and diffusion in a detector according to the prior art;

- Figure 2 illustrates changes in detectivity
10 limited by the dark current as a function of the thickness of the detector zone in a semiconductor-based quantum detector. The curve 2a pertains to a prior art quantum detector. The curve 2b pertains to a detector according to the invention;

15 - Figure 3 illustrates a first exemplary photoconductor detector according to the invention;

- Figure 4 illustrates a second exemplary photoconductor detector according to the invention;

20 - Figure 5 illustrates a first exemplary photovoltaic detector according to the invention;

- Figure 6 gives a schematic view of the energy levels defining the valency bands and the conduction bands of the set of semiconductor materials used in an exemplary photoconductor detector according to the
25 invention;

- Figure 7 gives a schematic view of the energy levels defining the valency bands and the conduction bands of the set of semiconductor materials used in an exemplary photovoltaic detector according to the
30 invention, with a type III heterostructure;

- Figure 8 gives a schematic view of the energy levels defining the valency bands and the conduction bands of the set of semiconductor materials used in an exemplary photovoltaic detector with a type II
35 heterostructure;

- Figure 9 gives a schematic view of the energy levels defining the valency bands and the conduction bands of the set of semiconductor materials used in an exemplary type I photovoltaic detector.

5 MORE DETAILED DESCRIPTION

According to one variant of the invention, the quantum structure detector working in the infrared range functions in photoconductor mode as shown in Figure 3. A substrate S supports a stack of
10 constituent layers of the detector. More specifically, this stack of layers comprises:

- a layer of large-gap, non-doped semiconductor material SGG₁;
- a layer of small-gap, non-doped semiconductor
15 material SPG;
- a layer of large-gap, non-doped semiconductor material SGG₂, whose surface has a grating R₁ in raised relief to provide for efficient coupling between the electromagnetic wave to be detected and the detector
20 zone constituted in the present case by the layer of material SPG.

These electron-hole pairs remain confined in the detector zone as shown in Figure 6 which shows an exemplary energy-level diagram of semiconductor
25 materials SGG₁, SPG and SGG₂. The energy level E_{vp} is higher than the energy levels E_{vg1} and E_{vg2} while the energy level E_{gp} is lower than the energy level E_{cg1} and E_{cg2}.

Ohmic contacts C₁ and C₂ are made at the detector
30 zone in order to measure the variations in resistance of said detector zone at the appearance of the electron-hole pairs due to the incident photons.

Figure 3 illustrates a detector in which the grating is transparent to incident light. Figure 4
35 describes another variant of the invention in which the

grating supports a metal layer Me, the light crossing the substrate.

Advantageously, this type of detector may include a guiding layer included in the SGG1 part to increase the interaction between the wave and the SGP part.

According to another variant of the invention, the detector works as a photovoltaic detector. As shown in Figure 5, it may advantageously include:

- a substrate constituted by a n-doped semiconductor material Sn;
- a layer of large-gap semiconductor material with n-type doping, SGG1;
- a layer of small-gap, non-doped semiconductor material SGP;
- a layer of large-gap, p-doped semiconductor material SGG1, whose surface has a grating in raised relief to provide for efficient coupling between the wave to be detected and the detector zone constituted by the layer of material SPG.

In this configuration, the movements of the free carriers take place perpendicularly to the plane of the layers and the ohmic contacts C_3 and C_4 are provided on either side of the stack of layers. The ohmic contact C_3 may be typically obtained by the metallization of the coupling grating and the setting up of a contact at the metallization (Me + CE).

To provide for the conveyance of the free carriers created in the stack of layers mentioned above, several alternatives may be envisaged.

A first variant of a photoconductor detector uses a heterostructure known in the literature as a type III heterostructure (C. Weisbuch and B. Vinter, "Quantum semiconductor structures", Academic Press). In this structure, the bottom of the conduction band of the small-gap semiconductor is located at the top of the valency band of the large-gap semiconductors. Figure 7

gives a schematic view of the gaps of the different semiconductor materials used in this type of heterostructure. The incident photons create electron-hole pairs on either side of the gap of the small-gap material SPG, this gap being defined by the maximum energy of the valency band E_{VP} and the minimum energy of the conduction band E_{CP} . Two barrier layers constituted by materials having very large gaps must be interposed between the layers of materials SGG_{1n}/SPG and SPG/SGG_{2p} . The materials with very large gaps have gaps defined by the energy levels E_{VT1} and E_{CT1} on the one hand and E_{VT2} and E_{CT2} on the other hand. E_{VT1} and E_{VT2} are lower than E_{CP} , E_{CT1} and E_{CT2} may be higher than E_{CG1} and E_{CG2} . In this configuration, the energy levels of the large-gap materials are such that the level E_{VG1} is lower than the level E_{VG2} , the level E_{CG1} being also lower than the level E_{CG2} since the material SGG_1 is n-doped while the material SGG_2 is p-doped.

Another variant of a photodetector detector uses a type II heterostructure whose energy-level diagram is illustrated in Figure 8. In this type of heterostructure, one of the types of carriers (the electrons in the example of Figure 8) remains blocked within the small-gap material SPG and may give rise to an internal photovoltaic effect.

In the heterostructure of Figure 8, the energy level E_{CP} is higher than the two energy levels E_{VG1} and E_{VG2} and the electrons remain confined within the conduction band of the small-gap material SPG.

The holes may circulate towards the p-doped semiconductor material, the material SGG_2 , and thus generate an internal photovoltaic effect.

According to a third variant of a photoconductor detector, it is possible to use a type I heterostructure whose energy-level diagram is shown in Figure 9. The large-gap semiconductor materials are

very highly doped and the maximum energy levels of the valency bands are such that $E_{VG1} < E_{VG} < E_{VG2}$.

The minimum energy levels of the conduction bands are such that:

$$E_{CG1} < E_{CG} < E_{CG2}$$

The electron-hole pairs created may thus be emitted by tunnel effect through the doped zone.

In general, all the constituent layers of the detectors according to the invention may be obtained by any technique known to those skilled in the art. However, in order to eliminate the electrical effects which are sources of noise, the $SGG_1/SPG/SGG_2$ structure should be crystallized and therefore obtained by molecular beam epitaxy or by vapor phase deposition. The semiconductor systems possible are for example GaAlSb/InAsSb/GaSb, CdTe/HgCdTe/CdTe, PbS/PbSnSe/PbS, etc.

Exemplary embodiment of a photoconductor detector

The semiconductor materials are the following:

SGG₁: GaSb
SPG: InAsSb
SGG₂: AlSb

The stacking of the layers is done with a lattice matching, i.e. in conditions where the distances between atoms are almost equal in all the materials. The following epitaxy is obtained:

Starting from a GaSb substrate, a GaSb layer of the order of 0.2 μm is epitaxially grown.

On this layer of material SGG₁, a 100 Å layer of AlAs_{0.08}Sb_{0.92} is made with a lattice matching with the GaSb layer, and forms a barrier for the electrons created in InAsSb. Then, a detector layer of InAs_{0.85}Sb_{0.15} is created with a thickness of 0.1 μm then again a 100 Å layer of AlAs_{0.08}Sb_{0.92} and finally a 0.6 μm layer of GaSb.

The composition of the InAsSb layer is chosen to obtain a cutoff wavelength (namely InAs_{0.85}Sb_{0.15}) of 5.1 μm .

5 A grating is etched to obtain a resonance of about 5 μm , i.e. for a grating period of 1.52 μm . The depth of the grating is 0.3 μm .

With this conditions, the maximum quantum yield is 80% despite a very small thickness of 0.1 μm for the detector zone.

10 Without a coupling grating, a 1 μm layer is needed to obtain an identical quantum yield leading to noise equivalent temperature NETD of 150 mK. By lowering the thickness of the detector layer to 0.1 μm , the detectivity is increased by a factor of 3 leading to an
15 NETD of 50 mK.

Exemplary embodiment of a photovoltaic detector

The photovoltaic detector is defined on a substrate of GaSb with n-type doping.

20 A 1 μm layer of GaSb with n-type doping is epitaxially grown on this substrate. Then a layer of about 50 Å of AlAs_{0.08}Sb_{0.92} is used to prevent the InAsSb/GaSb heterostructure from behaving like an ohmic contact. A detector layer of InAs_{0.85}Sb_{0.15} with a thickness of 0.1 μm is epitaxially grown, followed by a
25 50 Å layer of AlAs_{0.08}Sb_{0.92} and a 1 μm layer of GaSb with p-type doping. This heterostructure is a type III heterostructure and enables the electrons and holes to be emitted out of the detector zone. A grating identical to that of the example of the photoconductor
30 detector described here above is etched on the GaSb layer with p-type doping. Then a layer of metal (for example gold) is vapor-deposited on the grating as an electrical contact layer. The improvement of the performance characteristics of this photovoltaic
35 detector with respect to the prior art photovoltaic

detector is the same as that mentioned in the case of photoconductor detectors.



WHAT IS CLAIMED IS:

1. An optical wave detector with quantum structure comprising a stack of layers of semiconductor materials on a substrate (S) with an electromagnetic wave
5 detection zone, wherein the stack of layers comprises a layer of semiconductor material (SPG) with low gap energy constituting the detecting zone, contained between two layers of a semiconductor material (SGG1) and (SGG2) with high gap energy, and wherein the
10 detector comprises a coupling grating on the stack of layers to obtain efficient coupling between the optical wave to be detected and the detector zone.

2. A detector with quantum structure according to claim 1, wherein the thickness of the detector zone is
15 of the order of 1000 Å.

3. A detector with quantum structure according to claim 1, comprising two insulating semiconductor materials (SGG1) and (SGG2) and means to measure variations in resistivity of the layer of semiconductor
20 material (SPG).

4. A detector with quantum structure according to claim 1, comprising a semiconductor material (SGG1) with n type doping, a semiconductor material (SGG2) with p type doping and voltage measurement means
25 located on either side of the stack of layers.

5. A detector with quantum structure according to claim 1, comprising two barrier layers of semiconductor materials with very large gap (STG₁) and (STG₂) located at the interfaces of the layers of materials
30 (SGG1)/(STG) and (SGG2)/(SPG).

6. A detector with quantum structure according to claim 1, wherein the coupling grating is etched in the layer of semiconductor material (SGG2).

7. A detector with quantum structure according to
35 claim 1, comprising a layer of semiconductor material (SG) contained between the substrate (S) and the stack



of layers of semiconductor materials (SGG1)/(SPG)/(SGG2), the material (SG) having a refraction index that is smaller than that of the substrate (S) to confine the optical wave in the stack
5 of layers.

8. A detector with quantum structure according to claim 1, wherein the stack of semiconductor materials (SGG1)/(SPG)/(SGG2) is of the GaAlSb/InAsSb/GaSb type or CdTe/HgCdTe/CdTe type or PbS/PbSnSe/PbS type.