

FRONT-SIDE IMAGER AND PROCESS FOR MANUFACTURING SUCH AN IMAGER

FIELD OF THE INVENTION

5 The present invention relates to a front-side imager, and to a process for manufacturing such an imager.

PRIOR ART

Document US 2016/0118431 describes a front-side imager.

10 As illustrated in figure 1, said imager comprises a semiconductor-on-insulator (SOI) substrate comprising, from its back side to its front side, a silicon carrier substrate 1' having a certain dopant level, a layer 2' of silicon oxide called the buried oxide (BOX), and a layer 3' called the active silicon layer having a dopant level that is able to be different from that of the carrier layer 1', in which layer a matrix array of photodiodes is defined,
15 each photodiode defining one pixel.

According to one embodiment, the buried oxide is chosen to be relatively thin (i.e. to have a thickness smaller than 100 nm, and in particular of about 20 nm) in order to play the role of the dielectric of a capacitor. That portion of the substrate which is located below the buried oxide is biased to a voltage different from the voltage of the active layer, this
20 allowing the interface between the dielectric layer and this active layer to be passivated.

The voltage to be applied to that portion of the substrate which is located under the BOX depends on the thickness of the latter. The potential difference to be applied is proportional to the thickness of the buried oxide.

Inversely, if the buried oxide is chosen to be relatively thick (i.e. to have a thickness
25 of about 100 to 200 nm or more), it has reflective optical properties and allows incident photons to be reflected so as to confine them in the active layer, in particular in the case of photons the wavelength of which is in the range of the near infrared.

The optimal thickness ranges for each of these two functions do not coincide, and the skilled person is required to make a compromise between the reflectivity of the buried
30 oxide and his ability to polarize each pixel by applying a low potential difference between the active layer and the substrate.

DISCLOSURE OF THE INVENTION

Embodiments of the invention seek to design a front-side imager that can perform better than existing imagers, and in particular a substrate from which said imager may be obtained.

Preferably, this substrate must be able to be fabricated at low cost.

A first aspect of the invention relates to a front-side imager comprising in succession, from the back side to the front side of said front-side imager:

- a semiconductor carrier substrate,
- a first electrically insulating separating layer, and
- a single-crystal semiconductor layer, called the active layer, comprising a matrix array of photodiodes,

said imager being characterized in that it comprises, between the carrier substrate and the first electrically insulating layer:

- a second electrically insulating separating layer, and
- a second semiconductor or electrically conductive layer, called the intermediate layer, arranged between the second separating layer and the first separating layer, the second separating layer being thicker than the first separating layer,

and in that the imager furthermore comprises, on the active layer, a layer called the optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

By “front side” what is meant in the present text is that side of the imager which is intended to be exposed to light radiation, which side is located on the same side of the structure as the associated electronic components.

The first separating layer advantageously has a thickness comprised between 10 and 100 nm.

The second separating layer advantageously has a thickness comprised between 100 and 300 nm.

According to one embodiment, the intermediate layer is made of a doped polycrystalline or amorphous material.

According to one embodiment, the intermediate layer is made of doped silicon.

Alternatively, the intermediate layer is made of a metal.

The intermediate layer advantageously has a thickness comprised between 20 and 150 nm.

According to one embodiment, the active layer comprises a silicon seed layer.

According to another embodiment, the seed layer is a silicon-germanium layer.

According to one embodiment, the active layer furthermore comprises a single-crystal layer of silicon-germanium on the seed layer.

Particularly advantageously, the germanium content in the silicon-germanium layer is lower than or equal to 10%.

Preferably, the thickness of the silicon-germanium layer is smaller than a critical thickness defined as being a thickness beyond which the silicon-germanium relaxes.

According to another embodiment, the active layer furthermore comprises a single-crystal layer of silicon on the seed layer.

According to one embodiment, the substrate furthermore comprises, on the active layer, a layer called the optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

Advantageously, said optical confinement layer comprises a layer of titanium nitride between two layers of silicon oxide.

According to one embodiment, each photodiode is separated from an adjacent photodiode by at least one electrically isolating trench extending up to the first electrically insulating layer.

Advantageously, said trench comprises an electrically conductive or semiconductor via extending up to the intermediate layer between walls made of an electrically insulating material.

According to one embodiment, said at least one trench extends through the optical confinement layer.

According to one embodiment, each trench comprises a first wall extending up to the intermediate layer and a second wall extending at least partially into the second separating layer so as to electrically isolate a segment of the intermediate layer, the electrically conductive or semiconductor via being electrically connected to said segment of the intermediate layer.

The imager such as described above is formed from a substrate for a front-side imager, comprising in succession:

- the semiconductor carrier substrate,
- the first electrically insulating separating layer, and
- a single-crystal semiconductor layer, called the seed layer, which is suitable for epitaxial growth of a single-crystal semiconductor layer,

said substrate furthermore comprising, between the carrier substrate and the first electrically insulating layer:

- the second electrically insulating separating layer, and
- the second semiconductor or electrically conductive layer, called the intermediate layer, arranged between the second separating layer and the first separating layer, the second separating layer being thicker than the first separating layer.

According to one embodiment, the seed layer is a silicon layer.

According to another embodiment, the seed layer is a silicon-germanium layer.

According to one embodiment, the substrate furthermore comprises a silicon-germanium single-crystal layer on the seed layer, said silicon-germanium layer forming, with the seed layer, the active layer of the imager.

According to another embodiment, the substrate furthermore comprises a silicon single-crystal layer on the seed layer, said silicon layer forming, with the seed layer, the active layer of the imager.

According to a second aspect of the present invention, said substrate may be fabricated using a process comprising the following steps:

- providing a first donor substrate,
- forming a weakened zone in said first donor substrate, so as to delineate a first semiconductor layer,
- transferring said first layer to a semiconductor carrier substrate, an electrically insulating layer being at the interface between the donor substrate and the carrier substrate so as to form a structure comprising the carrier substrate, the electrically insulating layer, and the transferred layer,
- providing a second donor substrate,
- forming a weakened zone in said second donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure
- forming a layer called the optical confinement layer on the active layer, said optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

According to a third aspect of the present invention, the substrate may be fabricated using a process comprising the following steps:

- forming a structure by depositing an electrically conductive or semiconductor layer on a carrier substrate covered with an electrically insulating layer,
- providing a donor substrate,
- forming a weakened zone in said donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure
- forming a layer called the optical confinement layer on the active layer, said optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

Another subject of the invention relates to a process for fabricating a front-side imager such as described above.

According to one embodiment, said fabricating process comprises the following steps:

- providing a first donor substrate,
- forming a weakened zone in said first donor substrate, so as to delineate a first semiconductor layer,
- transferring said first layer to a semiconductor carrier substrate, an electrically insulating layer being at the interface between the donor substrate and the carrier

substrate so as to form a structure comprising the carrier substrate, the electrically insulating layer, and the transferred layer,

- providing a second donor substrate,
- forming a weakened zone in said second donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure,
- growing epitaxially a single-crystal semiconductor layer on the transferred single-crystal semiconductor layer, said epitaxial single-crystal semiconductor layer forming, with the transferred single-crystal semiconductor layer, an active layer of the imager.

According to one alternative embodiment, said fabricating process comprises the following steps:

- forming a structure by depositing an electrically conductive or semiconductor layer on a carrier substrate covered with an electrically insulating layer,
- providing a donor substrate,
- forming a weakened zone in said donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure,
- growing epitaxially a single-crystal semiconductor layer on the transferred single-crystal semiconductor layer, said epitaxial single-crystal semiconductor layer forming, with the transferred single-crystal semiconductor layer, an active layer of the imager.

Said processes furthermore comprise a step of forming a matrix array of photodiodes in the active layer.

Moreover, a layer called the optical confinement layer may be formed on the active layer, said optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

DESCRIPTION OF THE FIGURES

Other features and advantages of the invention will emerge from the detailed description which follows, with reference to the appended drawings in which:

- figure 1 is a cross-sectional view of an SOI substrate for a front-side imager such as described in document US 2016/0118431;
- figure 2 is a cross-sectional view of an SOI substrate, ready for epitaxy to form the active layer of a front-side imager according to the invention;

- figures 3A to 3E schematically illustrate the main steps of a process for fabricating the substrate of figure 2,

- figures 4A to 4D schematically illustrate the main steps of another process for fabricating the substrate of figure 2,

5 - figure 5 illustrates the substrate obtained after epitaxial growth of the active layer on the substrate of figure 2,

- figure 6 illustrates the substrate obtained after forming electrically isolating trenches in the substrate of figure 5 in order to singulate each pixel of the imager,

10 - figure 7A illustrates the substrate obtained after forming an optical confinement layer on the substrate of figure 6,

- figure 7B illustrates the substrate obtained after forming an optical confinement layer on the substrate of figure 5 and forming electrically isolating trenches in said substrate,

15 - figures 8 and 9 illustrate variants of the substrate of figure 6, in which each trench comprises a semiconductor via making contact with the intermediate layer.

To make the drawings clearer, the various layers have not necessarily been shown to scale.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

20 Contrary to the substrate of figure 1, an imager substrate according to the invention comprises a stack comprising two electrically insulating separating layers separated by a semiconductor or electrically conductive layer called the intermediate layer. The stack is interposed between the carrier substrate and the active layer, and it is configured to reflect photons that pass through the active layer toward the same active layer.

25 The carrier substrate is generally obtained by slicing a single-crystal ingot. Said substrate essentially plays the role of mechanical carrier of the imager. The carrier substrate may comprise a material chosen from silicon, III-V semiconductors, glass, silica, sapphire, alumina, aluminum nitride, silicon carbide or even a ceramic or a metal alloy. Advantageously, the carrier substrate is made of silicon. Its doping (if it is a question of
30 silicon), nature and characteristics may be optimized in order to integrate, in a hybrid way, in the form of a system-on-chip, electronic devices other than the imager. Said doping of the substrate may be uniform throughout the thickness of the material or limited to one segment thereof. Preferably, the doped zone is adjacent to one of the two separating layers.

35 The active layer comprises a single-crystal semiconductor and is intended to receive a matrix array of photodiodes that allow images to be captured.

The two separating layers on either side of the intermediate layer have different thicknesses and play different roles in the operation of the imager.

The first separating layer is located on the side of the front side, and it is thinner than the second separating layer, which is located on the side of the back side.

The role of the first separating layer is to allow a bias to be transferred from the intermediate layer to the active layer. The role of the second separating layer is to
 5 electrically insulate the intermediate layer from the substrate, and to allow the stack of the layers separating the active layer from the carrier substrate to have a suitable reflectivity with respect to photons coming from the active layer.

Each of the two separating layers is made from an electrically insulating material, such as a dielectric material, for example an oxide, such as a thermal or deposited silicon
 10 oxide, or even an oxynitride. The structure comprising these two electrically insulating separating layers may then be qualified a "double BOX", i.e. a "double buried oxide".

On the side of its front side, the substrate comprises a seed layer on the first separating layer, said seed layer being a single-crystal semiconductor layer suitable for the epitaxial growth of a single-crystal semiconductor layer intended to form, with the seed
 15 layer, the active layer of the imager.

The material of the seed layer is chosen depending on the material of the epitaxial layer, and in particular has a lattice parameter suitable for allowing the growth of the epitaxial layer while preventing or at the very least minimizing the generation of crystal defects such as dislocations.

20 The seed layer and the epitaxial layer may be made of the same material (homoepitaxy) or two different materials (heteroepitaxy).

The epitaxial layer may be made of silicon. In this case, the seed layer is advantageously made of silicon.

Preferably, the epitaxial layer is made of silicon-germanium (SiGe) because silicon-
 25 germanium has an optical absorption coefficient higher than that of silicon, in particular in the infrared, this absorption coefficient being proportional to the concentration of germanium. The seed layer may then be made of silicon-germanium or of silicon. In the latter case, the design of the epitaxial layer must not take into account only the concentration of germanium but also the thickness of said layer. Specifically, if the SiGe
 30 layer is formed by epitaxy on a silicon seed layer, the lattice parameter of which is different from that of the silicon-germanium, the SiGe layer relaxes beyond a certain thickness, called the critical thickness. This relaxation results in the formation of dislocations within the SiGe layer. Such dislocations make the SiGe layer unsuitable for use as active layer in particular in an imager and must therefore be avoided. Now, the
 35 critical thickness is inversely proportional to the concentration of germanium. The thickness of the epitaxial layer and the concentration of germanium in said layer therefore result from a compromise between:

- on the one hand, a thickness sufficiently large to capture a maximum of photons at the wavelengths of the near infrared,

- on the other hand, a sufficient concentration of germanium to increase the ability to absorb photons with the active layer, in particular in the near infrared, and

5 - lastly, a limited thickness (dependent on concentration), smaller than the critical thickness, in order to prevent the relaxation of the silicon-germanium and the creation of crystal defects (dislocations) that results therefrom.

Typically, it is sought to maximize the thickness and the concentration of germanium of the epitaxial layer in order to obtain the best possible absorption in the infrared.
10 Preferably, the germanium content of the active layer is lower than or equal to 10%. Specifically, the critical thickness of a layer of $\text{Si}_{0.9}\text{Ge}_{0.1}$ is about a few microns, this being suitable for the active layer of a front-side imager.

The intermediate layer may be a semiconductor or even an electrically conductive material. Specifically, the role of this intermediate layer is to allow the active layer to be
15 biased from behind, in other words via a zone placed between the carrier substrate and the second electrically insulating layer. Such a bias allows a potential difference to be applied between the active layer and the buried intermediate layer.

The intermediate layer may be single-crystal but this is not indispensable because it is neither sought to achieve the ability to conduct electrons through this layer, nor any
20 other electronic property such as commonly considered for applications other than that of imagers, but merely to achieve the ability to modify the electrical potential of the active layer on the periphery of the first separating layer.

The intermediate layer may thus be polycrystalline and/or amorphous, this making it less expensive to fabricate, and/or a metal. This layer may be doped to a greater or lesser
25 extent so as to ensure it is able to be biased. A semiconductor intermediate layer is advantageously made of silicon. Said layer then typically has a thickness comprised between 20 and 150 nm.

The first electrically insulating separating layer, which is interposed between the active layer and the intermediate layer, plays the role of the dielectric of a capacitor, and
30 thus allows the active layer to be biased on the periphery of the electrically insulating material. To this end, the first separating layer is chosen to be sufficiently thin to minimize the potential difference to be applied between the intermediate layer and the active layer. Typically, the thickness of the first separating layer is comprised between 10 and 100 nm.

The thickness of the first separating layer is in contrast too small to allow all the
35 photons that pass through the active layer, and in particular photons the wavelength of which is in the range of the near infrared, to be reflected. Therefore, photons that pass through the active layer are liable to pass through the first separating layer and the intermediate layer.

The role of the second separating layer is to induce a reflection of the photons, in particular photons the wavelength of which is in the range of the near infrared, toward the pixel formed in the active layer through the stack comprising: the second separating layer, the intermediate layer and the first separating layer. To this end, this second separating layer has a sufficiently large thickness to have a high reflectivity (or optical reflection coefficient) in particular in the field of the near infrared. Typically, the thickness of the second separating layer, which is for example made of silicon oxide, is comprised between 100 and 300 nm.

Figure 2 is a cross-sectional view of a substrate for a front-side imager according to one embodiment of the invention.

Said substrate comprises in succession, from its back side to its front side:

- a carrier substrate 1, preferably a semiconductor carrier substrate,
- the second electrically insulating separating layer 2b,
- the semiconductor intermediate layer 4,
- the first electrically insulating separating layer 2a, and
- the single-crystal semiconductor seed layer 3a.

Examples of processes for fabricating the substrate illustrated in figure 2 will now be described.

According to a first embodiment, which is illustrated in figures 3A-3E, the process for fabricating the substrate comprises two successive layer-transfer steps, in which the SmartCut™ process is for example implemented two times.

On the one hand, with reference to figure 3A, a first donor substrate 40 comprising a semiconductor intended to form the intermediate layer 4 is provided.

On the other hand, with reference to figure 3B, the carrier substrate 1 is provided, and the donor substrate is bonded to the carrier substrate, the second separating layer 2b being at the bonding interface. As shown in figure 3A, said layer 2b is for example formed beforehand on the surface of the first donor substrate 40 before the bonding. Alternatively, the layer 2b could be formed on the carrier substrate 1, or even formed by joining a layer formed on the first donor substrate and a layer formed on the carrier substrate.

Next, the first donor substrate is thinned so as to transfer a layer 4 of the semiconductor to the receiver substrate. This thinning may be carried out by polishing or etching of the semiconductor from the side opposite to the bonding interface. However, advantageously, before the bonding step, a weakened zone 41 is advantageously formed in the semiconductor so as to delineate a surface layer 4 to be transferred; said weakened zone may be formed by implanting atomic species such as hydrogen and/or helium (said implantation being schematically shown by arrows in figure 3A). After the bonding step, the thinning consists in detaching the first donor substrate 40 along the weakened zone 41, this leading to the transfer of the intermediate layer 4 to the carrier substrate 1 (see

figure 3C). Typically, the thickness of the transferred layer 4 is smaller than or equal to 300 nm. Optionally, a finishing treatment is carried out on the free surface of the transferred layer in order to promote the implementation of a new layer-transfer step, this treatment possibly leading to the transferred layer being thinned and its roughness decreased.

With reference to figure 3D, a second donor substrate 30 comprising a single-crystal material suitable for the epitaxial growth of the active layer and intended to form the seed layer 3a is moreover provided.

With reference to figure 3E, this second donor substrate is bonded to the intermediate layer 4 transferred beforehand to the carrier substrate 1, the first separating layer 2a being at the bonding interface. As shown in figure 3D, said layer 2a is for example formed beforehand on the surface of the second donor substrate 30 before the bonding. Alternatively, the layer 2a could be formed on the intermediate layer 4 after its transfer to the carrier substrate 1, or even formed by joining a layer formed on the second donor substrate and a layer formed on the transferred intermediate layer.

Next, the second donor substrate is thinned so as to transfer a layer 3a of the semiconductor to the receiver substrate, this allowing the substrate shown in figure 2 to be obtained. This thinning may be carried out by polishing or etching the semiconductor so as to obtain the thickness and surface finish desired for the epitaxy of the active layer. However, advantageously, before the bonding step, a weakened zone 31 is advantageously formed in the single-crystal semiconductor so as to delineate the seed layer 3a to be transferred. After the bonding step, the thinning consists in detaching the second donor substrate 30 along the weakened zone 31, this leading to the transfer of the seed layer 3a to the structure consisting of the carrier substrate 1, of the second separating layer 2b and of the intermediate layer 4. Typically, the thickness of the transferred seed layer is smaller than or equal to 300 nm. Optionally, a finishing treatment is carried out on the free surface of the transferred seed layer in order to promote the implementation of the epitaxy, this treatment possibly leading to the transferred layer being thinned and/or its roughness decreased.

According to a second embodiment, illustrated in figures 4A-4D, the process for fabricating the substrate comprises a step of depositing the intermediate layer (instead of transferring said layer from a donor substrate) and a single layer-transfer step, to form the seed layer.

This second embodiment of the process takes advantage of the fact that the semiconductor intermediate layer does not have an optical or electronic function and may therefore be made from a material that is not single-crystal but polycrystalline and/or amorphous. Thus, the intermediate layer may be formed by deposition on the subjacent second electrically insulating layer 2b.

With reference to figure 4A, the carrier substrate 1 covered with the second separating layer 2b is provided. Said layer 2b is typically formed by thermal oxidation of the carrier substrate 1 if the latter is made of silicon. Said layer may also be formed by chemical vapor deposition (CVD), which may then possibly require a treatment aiming to decrease its roughness to be carried out.

With reference to figure 4B, the intermediate layer 4, which is for example made of polysilicon and/or amorphous silicon, is deposited. This deposition may be achieved by CVD or by epitaxy at various temperatures (ranging from 300°C to more than 800°C depending on the techniques used). This deposition may be followed by a smoothing treatment, for example a plasma treatment, or polish of the layer 4 in order to obtain a surface finish suitable for bonding then transferring the seed layer.

With reference to figure 4C, a donor substrate 30 comprising a single-crystal material suitable for the epitaxial growth of the active layer and intended to form the seed layer 3a is provided. According to one embodiment, the seed layer 3a is delineated by a weakened zone 31 formed by implanting atomic species, such as hydrogen and/or helium.

With reference to figure 4D, this donor substrate 30 is bonded to the intermediate layer 4 deposited beforehand on the carrier substrate 1, the first separating layer 2a being at the bonding interface. As shown in figure 4C, said layer 2a is for example formed beforehand on the surface of the donor substrate 30 before the bonding. Alternatively, the layer 2a could be formed on the intermediate layer 4 after its deposition on the carrier substrate 1, or even formed by joining a layer formed on the donor substrate and a layer formed on the deposited intermediate layer.

Next, the donor substrate 30 is thinned so as to transfer the layer 3a to the intermediate layer 4, this allowing the substrate shown in figure 2 to be obtained. Advantageously, the thinning consists in detaching the donor substrate 30 along the weakened zone 31. Alternatively, the thinning could be carried out by polishing or etching the donor substrate from the side opposite to the bonding interface so as to obtain the thickness and surface finish desired for the epitaxy of the active layer. Typically, the thickness of the transferred seed layer is smaller than or equal to 300 nm. Optionally, a finishing treatment is carried out on the free surface of the transferred seed layer in order to promote the implementation of the epitaxy, this treatment possibly leading to the transferred layer being thinned and/or its roughness decreased.

This second embodiment of the process is particularly advantageous in that it is less expensive since it involves a single layer-transfer step instead of two.

Whatever the process for fabricating the structure illustrated in figure 2, a layer 3b of silicon-germanium or of silicon is then grown epitaxially on the transferred seed layer 3a until the thickness desired for the active layer (see figure 5) is obtained, i.e. typically a thickness larger than or equal to 1 μm . The epitaxial layer 3b may be slightly doped.

The seed layer 3a and the epitaxial layer 3b together form the active layer 3. Since the thickness of the epitaxial layer 3b is clearly larger than the thickness of the seed layer 3a, the optical properties of the active layer are considered to be essentially those of the epitaxial layer 3b, even if the layers 3a and 3b are made of different materials.

5 Thus, for example, if the epitaxial layer is made of SiGe but the seed layer is not made of SiGe, for example when it is made of silicon, the silicon layer is sufficiently thin (of a thickness smaller than or equal to 300 nm) with respect to the thickness of the SiGe layer to not notably affect the properties of the active layer in terms of absorption in the infrared.

10 However, it is possible to modify the nature of the seed layer, for example by means of a thermal-mixing process. As known *per se*, said process comprises oxidizing a SiGe layer grown epitaxially on a silicon layer, said oxidation having the effect of consuming only the silicon (to form silicon oxide) and of making the germanium migrate toward the face opposite to the free surface of the SiGe layer. An SiO₂ layer is then obtained on the
15 surface, which may then be removed by etching.

With reference to figure 6, a plurality of electrically isolating trenches 5 that extend up to the first electrically insulating layer 2a are formed in the active layer 3. These trenches are known in the field of imagers as capacitive deep trench isolations (CDTIs). Each region of the active layer bounded by such trenches is intended to form one pixel of
20 the imager. To this end, a subsequent step of the process for fabricating the imager is to form a photodiode (not shown) in said region. Processes for fabricating trenches and photodiodes are known to those skilled in the art and will therefore not be described in detail in the present text.

According to one optional but advantageous embodiment, with reference to figure
25 7A, the active layer 3 in which the trench isolations 5 have been formed is covered with an optical confinement layer 6 having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side. Said optical confinement layer 6 consists of a stack of layers that ensure such a selectivity of the reflectivity as a function of the direction of the incident photon.
30 According to one preferred embodiment, said optical confinement layer 6 comprises a layer of titanium nitride between two layers of silicon oxide having different thicknesses. One advantage of such a stack is that it is compatible with the processes used in microelectronics; the formation of the optical confinement layer may therefore be easily integrated into the process for manufacturing the imager. For example, the optical
35 confinement layer 6 comprises, from the front side to the back side, a layer of SiO₂ of 100 nm thickness, a layer of TiN of 10 nm thickness and a layer of SiO₂ of 200 nm thickness. The reflectivity of such a stack from the front side of the imager to the active layer is 0.5%, whereas its reflectivity from the active layer to the front side is 37%.

Said optical confinement layer 6 lets the radiation incident on the surface of the imager pass substantially without reflecting it, but in contrast reflects photons present in the active layer and reflected by the double BOX structure, this having the effect of trapping said photons in the active layer and of increasing their path length in the active layer. Said optical confinement layer thus allows the optical absorption of the active layer to be increased.

According to one embodiment illustrated in figure 7B, the electrically isolating trenches 5 also extending to the optical confinement layer 6. This configuration advantageously allows two adjacent pixels (or two adjacent imagers) to be electrically isolated from each other even in the confinement layer, in particular to avoid parasitic or shadowing effects.

According to one embodiment illustrated in figure 8, it is possible to bias each pixel entirely (i.e. to bias all the thickness thereof). To this end, each trench 5 is formed of an electrically conductive or semiconductor via 5a, for example made of silicon, extending up to the intermediate layer 4 between walls 5b made of an electrically insulating material. This arrangement is particularly advantageous in that it allows, with a single contact, the whole of the pixel to be biased since the semiconductor layers 5a and 4 are electrically connected.

Lastly, according to one embodiment illustrated in figure 9, it is possible to bias each pixel entirely and independently. Specifically, by adjusting the depth and the thicknesses of the interior and exterior walls 5b of each trench, each pixel may be biased independently of the adjacent pixel. For example, each pixel may be bounded on one side (right-hand side for the central pixel of figure 9) by a wall 5b made of a relatively thin electrically insulating material that extends up to the intermediate layer 4, and on the other side (left-hand side for the central pixel of figure 9) by a wall 5b made of relatively thick electrically insulating material that extends at least partially into the second separating layer 2b. The segment 4a of the intermediate layer 4 located under the pixel is electrically connected to the semiconductor layer 5a located on only one side of the pixel (right-hand side for the central pixel of figure 9) and is electrically isolated from the rest of the intermediate layer 4. Thus, each pixel may advantageously be addressed independently.

Although not shown in figures 8 and 9, the optical confinement layer could be present on the active layer and be passed through or not by the trenches 5 as shown in figures 7B and 7A.

Examples

Numerical simulations of optical absorption have been carried out for various substrates, according to the prior art (with a single layer of silicon oxide between the carrier substrate and the active layer, as illustrated in figure 1) and according to the invention (with a double BOX structure between the carrier substrate and the active layer,

as illustrated in figure 5). Said double BOX structure consists of the following stack, from the front side to the back side of the substrate:

- first separating layer 2a: SiO₂, 40 nm
- semiconductor intermediate layer 4: polysilicon, 100 nm
- 5 - second separating layer 2b: SiO₂, 150 nm

The reflectivity of such a stack is about 72% for an incident wavelength of 940 nm.

In these simulations, certain substrates were covered with an optical confinement layer having a reflectivity from the front side toward the active layer higher than the reflectivity from the active layer toward the front side. Said optical confinement layer consisted of the following stack, from the front side toward the back side of the substrate:

10 SiO₂, 100 nm / TiN, 10 nm / SiO₂, 200 nm.

The active layer consisted either of a silicon layer of 6 μm thickness, or of a SiGe layer of 2 μm thickness having a concentration of germanium equal to 10%.

The table below indicates the optical absorption coefficient in the active layer, for radiation of normal incidence (i.e. incidence perpendicular to the front side of the substrate) and having a wavelength of 940 nm. The simulation does not take into account the influence of diffraction or of refraction from the trenches separating the various pixels.

15

Optical confinement layer	No	No	No	Yes	Yes	Yes
Carrier substrate-active layer interface	SiO ₂ 30 nm	Double BOX	Double BOX	SiO ₂ 30 nm	Double BOX	Double BOX
Active layer	Si 6 μm	Si 6 μm	Si _{0.9} Ge _{0.1} 2 μm	Si 6 μm	Si 6 μm	Si _{0.9} Ge _{0.1} 2 μm
Optical absorption coefficient	33%	47%	49%	47%	68%	87%

A significant improvement in absorption is observed when a double BOX structure is used instead of a single layer of SiO₂. The optical absorption is further improved when the active layer is made of SiGe instead of silicon, and/or when an optical confinement layer that confines the photons in the active layer is added.

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REFERENCES

25 US 2016/0118431

CLAIMS

1. A front-side imager comprising in succession, from the back side to the front side of said front-side imager:

- a semiconductor carrier substrate,
- a first electrically insulating separating layer, and
- a single-crystal semiconductor layer, called the active layer, comprising a matrix array of photodiodes,

said imager being characterized in that it comprises, between the carrier substrate and the first electrically insulating layer:

- a second electrically insulating separating layer, and
- a second semiconductor or electrically conductive layer, called the intermediate layer, arranged between the second separating layer and the first separating layer, the second separating layer being thicker than the first separating layer,

and in that the imager furthermore comprises, on the active layer, a layer called the optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

2. The imager as claimed in claim 1, wherein the first separating layer has a thickness comprised between 10 and 100 nm.

3. The imager as claimed in either of claim 1 or 2, wherein the second separating layer has a thickness comprised between 100 and 300 nm.

4. The imager as claimed in one of claims 1 to 3, wherein the intermediate layer is made of a material among: doped polycrystalline or amorphous material, doped silicon, or metal.

5. The imager as claimed in one of claims 1 to 4, wherein the intermediate layer has a thickness comprised between 20 and 150 nm.

6. The imager as claimed in one of claims 1 to 5, wherein the active layer comprises a silicon seed layer.

7. The imager as claimed in one of claims 1 to 5, wherein the active layer comprises a silicon-germanium seed layer.

8. The imager as claimed in either of claim 6 or 7, wherein the active layer furthermore comprises a single-crystal layer of silicon-germanium on the seed layer.

9. The imager as claimed in claim 8, wherein the germanium content in the silicon-germanium layer is lower than or equal to 10%.

10. The imager as claimed in either of claim 8 or 9, wherein the thickness of the silicon-germanium layer is smaller than a critical thickness defined as being a thickness beyond which the silicon-germanium relaxes.

11. The imager as claimed in claim 6, wherein the active layer furthermore comprises a single-crystal layer of silicon on the seed layer.

12. The imager as claimed in claim 1, wherein said optical confinement layer comprises a layer of titanium nitride between two layers of silicon oxide.

13. The imager as claimed in one of claims 1 to 12, wherein each photodiode is separated from an adjacent photodiode by at least one electrically isolating trench extending up to the first electrically insulating layer.

14. The imager as claimed in claim 13, wherein said trench comprises an electrically conductive or semiconductor via extending up to the intermediate layer between walls made of an electrically insulating material.

15. The imager as claimed in either of claims 14 and 13 when dependent on claim 13, wherein said at least one trench extends through the optical confinement layer.

16. The imager as claimed in claim 14, wherein each trench comprises a first wall extending up to the intermediate layer and a second wall extending at least partially into the second separating layer so as to electrically isolate a segment of the intermediate layer, the electrically conductive or semiconductor via being electrically connected to said segment of the intermediate layer.

17. A process for manufacturing a front-side imager, comprising the following steps:

- providing a first donor substrate,
- forming a weakened zone in said first donor substrate, so as to delineate a first semiconductor layer,
- transferring said first layer to a semiconductor carrier substrate, an electrically insulating layer being at the interface between the donor substrate and the carrier substrate so as to form

a structure comprising the carrier substrate, the electrically insulating layer, and the transferred layer,

- providing a second donor substrate,
- forming a weakened zone in said second donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure,
- growing epitaxially a single-crystal semiconductor layer on the transferred single-crystal semiconductor layer, said epitaxial single-crystal semiconductor layer forming, with the transferred single-crystal semiconductor layer, an active layer of the imager
- forming a layer called the optical confinement layer on the active layer, said optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

18. A process for manufacturing a front-side imager, comprising the following steps:

- forming a structure by depositing an electrically conductive or semiconductor layer on a carrier substrate covered with an electrically insulating layer,
- providing a donor substrate,
- forming a weakened zone in said donor substrate, so as to delineate a single-crystal semiconductor layer,
- transferring said single-crystal semiconductor layer to the structure, an electrically insulating layer being at the interface between the second donor substrate and the structure,
- growing epitaxially a single-crystal semiconductor layer on the transferred single-crystal semiconductor layer, said epitaxial single-crystal semiconductor layer forming, with the transferred single-crystal semiconductor layer, an active layer of the imager
- forming a layer called the optical confinement layer on the active layer, said optical confinement layer having a coefficient of optical reflection from the front side toward the active layer higher than the coefficient of reflection from the active layer toward the front side.

19. The process as claimed in either of claim 17 or 18, furthermore comprising forming a matrix array of photodiodes in the active layer.