

METHOD AND DEVICE FOR WAVELENGTH-SENSITIVE PHOTO-SENSING USING MULTIPLE PN-JUNCTIONS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit and priority from U.S. provisional application no. 60/561,152 filed April 12, 2004, the contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to photo-sensing, and more particularly to methods and devices for wavelength-sensitive photo-sensing using multiple *pn*-junctions.

BACKGROUND OF THE INVENTION

[0003] Wavelength-sensitive photo-sensing (often referred to as color sensing) has applications in a wide range of fields such as medicine and biology, the food, printing, and cosmetics industries, and the like. For example, in the study of cells and tissues, it may be necessary to monitor or detect the transmission and absorption of light of a certain bandwidth by cells and tissues under study.

[0004] Color of light can be sensed using *pn*-junction based photo-diodes. As is known, a *pn*-junction can form a photo-diode. When light is absorbed in a depletion region around a reversely biased *pn*-junction, free charge carriers are generated due to photoelectric effect. The photo-generated carriers can be detected by sensing either a current or a voltage across the *pn*-junction. The sensed current or voltage can indicate the intensity of light absorbed in the depletion region. Since longer wavelength light can penetrate deeper below the surface than shorter wavelength light, different wavelength bands of an incident light can be detected by positioning multiple *pn*-junctions at different depths in a semiconductor. In a spectrometric approach, the spectrum of light is divided into many narrow bands. In a colorimetric approach, the color of light is resolved

into three primary color components, such as blue, green and red (RGB), which penetrate increasingly deeper into a semiconductor. Thus, the color of light can be detected using a sensor having three or more appropriately positioned *pn*-junctions.

[0005] U.S. Patent No. 5,965,875 to Richard B. Merrill, entitled “Color separation in an active pixel cell imaging array using a triple-well structure”, which is incorporated herein by reference (referred herein as “Merrill I”) discloses a known color sensing device. Each photo-sensing cell or pixel of the device includes three well-shaped *pn*-junctions (referred to as a triple-well structure) formed in a semiconductor substrate. Each junction is at an appropriate depth so that the three spectral components of incident light can be detected by detecting currents from the respective *pn*-junctions. An array of pixels is formed in the device. The pixels are isolated by doped well regions. However, this device has some shortcomings. For example, the triple-well structures are formed by diffusion. As is known, it can be difficult to form a well-defined abrupt *pn*-junction by diffusion, particularly when it is deep. Thus, a color sensor based on the triple-well structure may have poor performance.

[0006] Moreover, the performance of such a device can be negatively affected by interference between adjacent *pn*-junctions in a cell or between adjacent cells. Such a cross-junction or cell interference can occur between two adjacent and closely disposed *pn*-junctions due to movement of free carriers from an area near one of the *pn*-junctions to an area near the other *pn*-junction. Further, it may be desirable that the size of each pixel in a sensing array is small and that the pixels are well isolated. It can be difficult to achieve good isolation and a small pixel size with triple-well structures. Manufacture limitations or other performance considerations may also make it difficult to reduce the size of a triple-well structure.

[0007] U.S. Patent No. 6,632,701 to Richard B. Merrill, entitled “Vertical color filter detector group and array”, which is incorporated herein by reference, discloses a device in which the vertically-stacked *pn*-junctions are isolated by buried layers. In this device, the vertically stacked junctions in each pixel are well isolated. However, this device still suffers some of the shortcomings discussed above – it can be difficult to keep adjacent

pixels well isolated while limiting the size of each pixel. Further, it can be difficult and cumbersome to fabricate this device without advanced technology and specialized equipments.

[0008] Accordingly, there is a need for improved methods and devices for sensing color based on vertically-stacked *pn*-junctions.

SUMMARY OF THE INVENTION

[0009] A photo-sensing cell can include one or more insulation regions for laterally isolating adjacent regions in the cell and/or for laterally isolating the cell from an adjacent cell. The photo-sensing cell can be used alone or in an array of cells such as forming light sensing pixels in a color sensing device.

[0010] An insulation region can provide good isolation between different regions in a cell or between adjacent cells in a sensing array even when the cell or cells are small in size and closely disposed. Since insulation regions can be made laterally small, such as by employing the shallow trench isolation (STI) technique, the color sensing pixels can have small sizes with low or no cross-interference.

[0011] A sensing cell can be formed primarily by epitaxial growth to achieve good control of layer thickness, doping level, doping profile, and very abrupt *pn*-junctions with very well controlled features.

[0012] Accordingly, in an aspect of the present invention, a photo-sensing cell is provided. The photo-sensing cell has a substrate with a surface. A plurality of regions are formed in the substrate beneath the surface one below another and are alternatively doped of first and second conductive types, thus forming a plurality of *pn*-junctions at different depths relative to the surface. The depths are chosen for detection of light of respective wavelength bands incident on the surface. A conductive region is formed in the substrate and extends from the surface to an associated one of the plurality of regions. One or more insulation regions are formed in the substrate, each extending from the surface proximate and along the conductive region for laterally isolating the conductive region from an adjacent depletion region.

[0013] In another aspect of the present invention, there is provided a photo-sensing cell comprising a plurality of semiconductor layers formed epitaxially one on top of another. An insulation layer having a surface is formed on the semiconductor layers. The semiconductor layers are alternately doped of first and second conductive types, thus forming a plurality of *pn*-junctions at different depths relative to the surface of the insulation layer. The depths are selected for detection of light of respective predetermined wavelength bands incident on the surface. A plurality of conductors is also provided. Each conductor extends from one of the layers through the insulation layer for interconnection with an electrical interconnect.

[0014] In a further aspect of the present invention, there is provided a semiconductor device comprising one or more photo-sensing cells, each according to one of the two preceding paragraphs.

[0015] In yet another aspect of the present invention, there is provided a method of forming a semiconductor device. In this method, a plurality of layers are epitaxially grown on a wafer, one on top another and alternatively doped of first and second conductive types, thus forming a plurality of *pn*-junctions. An insulation layer is formed on the plurality of layers. The insulation layer has a surface and the depths of the *pn*-junctions relative to the surface are respectively chosen for detection of light of different wavelength bands incident on the surface. A conductor is placed on each one of one or more of the plurality of layers. The conductor extends from the each layer through the insulation layer.

[0016] In another aspect of the present invention, there is provided another method of forming a semiconductor device. This method includes epitaxially growing, on a first layer of a first conductive type, a second layer of an opposite, second conductive type, thus forming a first *pn*-junction. A first well region doped of the first conductive type is formed in the second layer, thus forming a second *pn*-junction. A second well region doped of the second conductive type is formed in the first well region, thus forming a third *pn*-junction. The *pn*-junctions are at respective depths relative to a surface of the second layer, chosen for detection of light of different wavelength bands incident on the

surface. The method further includes forming, in the second layer and away from the first well region, a conductive region doped of the first conductive type extending from the first layer through the second layer, and forming an isolation trench in the second layer proximate and along the conductive region for isolating the conductive region from a depletion region within in the second layer.

[0017] Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] In the figures, which illustrate, by way of example only, embodiments of the present invention,

[0019] **FIG. 1A** is a schematic cross-sectional view of a photo-sensing cell, exemplary of an embodiment of the present invention;

[0020] **FIG. 1B** is a schematic, partial cross-sectional view of a semiconductor device having a plurality of photo-sensing cells of **FIG. 1A**;

[0021] **FIG. 2** is a schematic, partial cross-sectional view of a semiconductor device having an exemplary implementation of the photo-sensing cell of **FIG. 1A**;

[0022] **FIG. 3** is a schematic cross-sectional view of another photo-sensing cell, exemplary of an embodiment of the present invention; and

[0023] **FIGS. 4 to 6** are respectively schematic, partial cross-sectional views of semiconductor devices incorporating the exemplary photo-sensing cell of **FIG. 3**.

DETAILED DESCRIPTION

[0024] In this description, the letters “N” and “P” are used to indicate the conductive types of doped semiconductor regions. The relative doping concentrations are indicated with trailing signs “+” and “-”. Alternatively, the terms “strongly doped”, “normally

doped” and “weakly doped” are used to indicate the relative doping concentrations.

[0025] FIG. 1A depicts schematically a photo-sensing cell 100 in a semiconductor device, exemplary of an embodiment of the present invention. Cell 100 includes a substrate 102 (partially shown) having a surface 104. A plurality of alternately doped regions 106, 108, 110 and 112 are formed in substrate 102 one below another beneath surface 104. Regions 106 and 108 are of *n*-type and regions 110 and 112 are of *p*-type. Thus, three *pn*-junctions 114, 116 and 118 are formed at respective depths, d_1 , d_2 and d_3 , relative to surface 104, where $d_1 < d_2 < d_3$. The depths are chosen so that incident light at three different wavelengths of surface 104 generates charge carriers in the depletion regions developed from the respective junctions in response to the light of the three different wavelength bands. For example, the depths may be chosen for detection of blue (B), green (G) and red (R) components of the incident light.

[0026] A conductive region 120 extends from region 118 to surface 104. Conductive region 120 can include a semiconductor more strongly doped than region 112.

[0027] Insulation regions 122A, 122B and 122C (also collectively and individually referred to as 122) each extends from surface 104 to region 118. Insulation region 122A extends proximate and along conductive region 120 to laterally isolate conductive region 120 from the depletion region developed from *pn*-junction 116.

[0028] As illustrated in FIG. 1B, which depicts two photo-sensing cells 100 arranged side by side, insulation regions 122B and 122C disposed on opposite ends of a cell 100 can laterally isolate each cell 100 from a neighbouring cell or cells. While only two cells 100 are depicted, it is understood that the number of photo-sensing cells formed on a device may vary. The photo-sensing cells may be arranged in a desirable pattern for imaging in one or two lateral dimensions.

[0029] Each insulation region 122 can include a trench filled with an insulating material such as undoped polysilicon or SiO₂. For example, the trench can have a SiO₂ coated wall and be filled with undoped polysilicon for easy fabrication and good insulation. One or two of insulation regions 122A, 122B and 122C may be omitted. For

example, when cell **100** is to be used alone, insulation regions **122B** and **122C** may be omitted. Each insulation region may extend deeper or shallower than is shown in **FIG. 1A**, depending on the application. A deeper insulation region may provide better isolation.

[0030] Insulation regions **122** may be formed using a standard or modified Shallow Trench Isolation (STI) technique.

[0031] Photo-sensing cell **100** has a number of electrical interconnects **124** respectively in communication with regions **106**, **108**, **110**, and **112** for detecting electrical signals respectively derived from the depletion regions developed around junctions **114**, **116**, and **118** so that incident light on surface **104** can be detected through electrical interconnects **124**. Each electrical interconnect **124** may include a conductor such as a metal. For example, interconnects **124** may be made of aluminium.

[0032] Cell **100** can be formed using any suitable materials and semiconductor fabrication techniques. Exemplary techniques that can be used in the fabrication of cell **100** are disclosed in Hong Xiao, *Introduction to Semiconductor Manufacturing Technology*, Prentice Hall, 2001, which is incorporated herein by reference, and Merrill I and Merrill II, *supra*. Suitable materials and fabrication techniques in a particular application can be readily selected and implemented by persons skilled in the art, after reviewing this description and references cited herein.

[0033] For example, region **112** may be formed by epitaxial growth on a semiconductor wafer (not shown). Region **108** may also be formed by epitaxial growth on region **112**. Each of regions **106**, **110**, **120** and **124** may be formed by diffusion, or by ion implantation followed with drive-in diffusion.

[0034] One of regions **108** and **112** may have a strongly-doped sub-region (not shown) formed at the interface of regions **108** and **112** between insulating trenches **122A** and **122C**, as will be discussed below, for limiting expansion of the depletion region developed from *pn*-junction **118** within the sub-region. As can be appreciated, an electrical path is formed in the sub-region which has a lower resistivity than those of the

adjacent regions.

[0035] Other regions or layers such as light shields, antireflective layers and insulation layers may be formed on substrate **102** above surface **104**. Such additional regions and layers can be readily determined by persons skilled in the art.

[0036] In operation, an applied voltage may reverse bias one or more of the *pn*-junctions **114**, **116** and **118**. A beam of light is incident on surface **104** and absorbed at different depths in substrate **102**, depending on the wavelengths of light. Free carriers may be generated in a depletion regions developed from one of *pn*-junctions **114**, **116** and **118** in response to incident light and produce an electrical signal such as a current or voltage in the electrical interconnects **124** in communication with the depletion region. The output signal is dependent on the amount of light absorbed in the depletion region. Since there are three depletion regions at three different depths, three different spectral components of the incident light can be detected.

[0037] The applied biasing voltages can be chosen to control the size of the depletion regions, for example, to adjust the spectral responses of the depletion regions. The operation of cell **100** is similar to the triple-well photo-sensor disclosed in U.S. Patent No. 5,965,875, *supra*, which provides further details on operating a triple-junction photo-sensing cell. Thus, detailed operation of cell **100** will not be discussed herein.

[0038] Conveniently, because conductive path **120** is provided between region **112** and surface **104**, region **108** can be formed by epitaxial growth on region **112**. Moreover, since it is not necessary to form region **108** by diffusion, the lateral size (in the horizontal direction as depicted) of cell **100** can be small, as compared to the size of a conventional triple-well color sensing cell. Further, as a conductive path such as conductive region **120** is isolated from adjacent *pn*-junctions extending along it by insulation regions **122**, cross-interference can be limited even when the lateral size of cell **100** is small. Thus, cell **100** can be made more compact than a photo-sensing cell based on the triple-well structure and still have good performance. Cells **100** can be advantageously used in a photo-sensing array such as an imaging device as pixels, where cross-interference between adjacent pixels are limited by insulation regions **122B** and **122C**. The photo-sensing

array or imaging device can thus have a high density of small pixels, resulting in high resolution.

[0039] As can now be appreciated, regions **122B** and **122C** can extend deeper than shown in **FIG. 1A**. For example, they may extend through region **112** for better insulation between adjacent cells **100**. In addition, **122C** can be located closer to **122A** by cutting through well regions **106** and **110** to further reduce the later size of cell **100**. It will be apparent to one skilled in the art that cell **100** has a simple structure and can be readily modified to suit various applications.

[0040] **FIG. 2** illustrates an example physical embodiment of cell **100**. Substrate **202** has a surface **204** and includes doped regions **206** (N^+), **208** (N), **210** (P) and **212** (P^-). The conductive region necessary for contacting region **212** includes a strongly doped contact region **220** (P^+). The insulating regions include insulating trenches **222**. The electrical interconnects include metal contacts **224**.

[0041] The additional regions or layers include a strongly doped p -type substrate layer **230** (P^+), a strongly doped n -type buried layer **232** (N^+) which can be considered a sub-region of region **208**, strongly doped contact regions **234** (N^+) and very strongly doped contact regions **236** (N^{++}) and **238** (P^{++}) in substrate **202** each extending from surface **204** for interconnection with a respective electrical interconnect **224**, and relatively strongly doped edge regions **240**, the benefit of which will become clear below.

[0042] For example, the layers and regions may have the following respective doping concentrations: about $1E18$ to $1E19\text{ cm}^{-3}$ for region **206**; $1E15$ to $1E16\text{ cm}^{-3}$ for region **208**; $1E17$ to $1E18\text{ cm}^{-3}$ for region **210**; $1E14$ to $1E15\text{ cm}^{-3}$ for region **212**; $1E17$ to $1E19\text{ cm}^{-3}$ for layer **230**; $1E18$ to $1E19\text{ cm}^{-3}$ for layer **232**; and at least $1E16$ to $1E17\text{ cm}^{-3}$ for edge regions **240**.

[0043] Region **206** may be relatively thin, such as about 0.04 to 0.06 microns thick. As can be appreciated by one skilled in the art, because it is so shallow, region **206** can have high sheet resistance. In such a case, providing two contact regions **236** at the opposite ends of region **206** can guard region **206** to optimize its breakdown voltage and

reduce the travel distance of photo-generated carriers within region 206.

[0044] Layer 208 may be about 4 to 6 microns thick. Layer 232 may be thinner, for example, having a thickness of about 1.8 microns.

[0045] It should be understood that the doping levels and thicknesses of the layers and regions in cell 200 may vary depending on the particular application and will not always be specified. When specific values are given, they are exemplary and for illustration purposes only.

[0046] As alluded to earlier, layer 232 is more strongly doped than its adjacent regions to limit expansion of the depletion region developed from pn -junction 218 within layer 232 and to form an electrical path in layer 232 which has a lower resistivity than those of the adjacent regions. Thus, photo-generated charge carriers can be more effectively collected from region 208.

[0047] As can be understood, cell 200 can be fabricated in various suitable manners. For example, cell 200 may be formed by first providing a strongly doped p -type wafer to form layer 230. The wafer may have any suitable size and thickness depending on the application. A relatively weakly doped p -type layer is epitaxially grown on layer 230 to form layer 212. A strongly doped n -type layer is implanted in a selected region in layer 212 to form buried layer 232. Due to the nature of the implantation technique, the implanted region may extend into layer 212, as depicted in FIG. 2. A weakly doped n -type layer is epitaxially grown on layers 212 and 232 to form layer 208. A shallow, doped p -type well is formed in layer 208 by diffusion to form region 210. A strongly doped n -type well is formed in region 210 by diffusion to form region 206. Region 210 has edge regions 240, which are also of p -type and are formed by a field implantation technique. The edge regions can prevent accidental field-induced inversion at surface 204.

[0048] Strongly doped contact regions such as contact regions 220, 234, 236 and 238 may be formed by diffusion with materials of appropriate conductive type and may extend to desired depths in a given application. Each strongly doped contact region may have a doping concentration higher than the surrounding region. For example, the deep

contact regions **220** and **234** may each have an average doping concentration of about $1\text{E}18$ to $1\text{E}19\text{ cm}^{-3}$ and the shallow contact regions **236** and **238** may each have a surface doping concentration of about $1\text{E}20\text{ cm}^{-3}$. As can be understood, the depth and doping level of each contact region depend on its purpose. For contacting low-lying regions (such as regions **208** and **212**), the contact regions (such as contact regions **220** and **234**) may be deeper. It is not necessary for a contact region to have a uniform doping concentration. For example, a deeper portion (e.g. regions **220** and **234**) of a contact region may have a lower doping concentration than a shallower portion (e.g., region **236** above region **234**, and region **238** above region **220**) of the contact region. The higher doping of the shallower portion allows good ohmic contact with a metal interconnect and the lower doping of the deeper portion allows for easier fabrication, such as by diffusion.

[0049] Conductive contact region **220** is formed away from well region **210** and extends through region **208**.

[0050] Insulating trenches **222** are formed in layer **208** by a STI technique or any other such similar method. Each insulating trench **222** may be formed by first etching a trench in layer **208**, oxidizing the trench wall to form a SiO_2 layer **242**, and filling the trench with a filler **244** such as polySi. Filling with polySi may be advantageous because relatively thick polySi can be quickly deposited. Further, polysilicon has a coefficient of thermal expansion very close to that of monocrystalline silicon, which is typically used for forming the semiconductor layers and regions. Therefore, mechanical stress in substrate **202**, which can be induced by different thermal expansion of different regions, can be reduced. Layer **242** may provide electrical insulation as well as make the surface the trench wall smooth. Trench **222** may be first etched using a dry etching technique and followed by a series of short, wet etching steps. After each etching step, oxidation growth may be performed to remove sharp edges. As can be appreciated, sharp edges may be undesirable because they produce strong electrical fields. After fabrication of trenches **222**, surface **204** may be planarized using a suitable technique such as Chemo-Mechanical Planarization (CMP).

[0051] In some applications, to minimize the lateral size of cell **200**, trenches **222**

may be formed before any diffusion is performed, for example, to form conductive region **220** or contact region **234**. The trenches **222** can be positioned to limit the lateral diffusion. In some other applications, trenches **222** may be formed late in the fabrication process. When formed late in the process, trenches **222** can still be positioned to limit cell size to a certain degree, for example, by “cutting through” regions formed by diffusion.

[0052] The metal contacts **224** are formed using a suitable metal such as an aluminium-based alloy including AlSiCu.

[0053] Additional layers and electronic structures including a protective cover (not shown) may be formed on surface **204**. For example, the cover may include an insulation layer, an antireflective (AR) filter for preventing internal reflection of light, and a metal shield for shielding external light. The cover may also have a window area with a reduced thickness such as about 100 Å or thinner, which is above and in substantial alignment with *pn*-junctions **214**, **216**, and **218** to allow more light to pass through. The window area should be made of a suitable material such as metal-oxide silicon (MOS) gate oxide, to not only provide good insulation and but also minimize generation-recombination phenomena at the Si-SiO₂ interface.

[0054] A further exemplary photo-sensing cell **300**, exemplary of another embodiment of the present invention is schematically illustrated in **FIG. 3**. Photo-sensing cell **300** includes a substrate **302**. Substrate **302** includes a plurality of semiconductor layers **306**, **308**, **310** and **312** formed one on top of another, which include *n*-type regions **306** and **308** and *p*-type regions **310** and **312**. Substrate **302** also has an insulation layer **322** formed on layers **306**, **308**, **310** and **312**. Insulation layer **322** has a surface **304**. The three *pn*-junctions **314**, **316** and **318** are formed at respective depths, d_1 , d_2 and d_3 , relative to surface **304**, where $d_1 < d_2 < d_3$, chosen as in cell **100**.

[0055] Each of layers **306**, **308**, **310** and **312** has an exposed top portion in contact with insulation layer **322**. Conductors **320A-320D** (also referred to collectively or individually as **320**) each extends from one of layers **306**, **308**, **310** and **312** to surface **304**. Each conductor **320** defines a conductive region and can be formed of a metal such as aluminium, copper, or the like. Conductors **320** form part of electrical interconnects in

communication with regions **306**, **308**, **310** and **312**, respectively, for detecting electrical signals respectively derived from the depletion regions so that incident light on surface **304** can be detected through conductors **320**.

[0056] Insulation layer **322** laterally isolates conductors **320** from each other and from the semiconductor layers, as well as isolating cell **300** from its environment. Insulation layer **122** can be formed of an insulating material such as SiO₂. As can be appreciated, a conductor **320** does not have to extend to surface **304**, and may otherwise extend through insulation layer **322** for interconnection with an electrical interconnect. For example, in an alternative embodiment, conductor **320D** may turn toward the right hand side.

[0057] Cell **300** can also be formed using any suitable materials and semiconductor fabrication techniques. Suitable materials and fabrication techniques in a particular application can be readily selected and implemented by persons skilled in the art, after reviewing this description and references cited herein. In particular, layers **306**, **308**, **310** and **312** may be formed by epitaxial growth followed by exposing top portions such as by etching so that insulation layer **322** can be next formed on the exposed portions.

[0058] Cell **300** can be operated in a similar manner as for cell **100** to detect wavelength components of light.

[0059] Cell **300** may have certain advantages over cell **100**. For example, the doping profiles in the regions of cell **300** can change more quickly than in cell **100** and thus can form much more abrupt *pn*-junctions. In general, cell **300** can be realized to have regions with well controlled properties such as thickness and doping profile. Further, it is not necessary to form insulating trenches in cell **300**, which may be time-consuming and expensive to form. One or more additional *pn*-junctions can be conveniently formed, if desired, without significantly increasing the size of the cell, such as by forming additional semiconductor layers on top of layer **306**.

[0060] As can be appreciated, it is not necessary that all of the semiconductor layers **306**, **308**, **310** and **312** are exposed to insulation layer **322**. For example, only the top two

layers **306** and **310** may be exposed. The electrical contacts for layers **308** and **312** can be provided from the side and the backside, respectively.

[0061] FIG. 4 illustrates an example physical embodiment **400** of cell **300**. A substrate **402** includes a wafer **430** (P^+) strongly doped of p -type. To form vertically aligned pn -junctions, a plurality of alternatively doped layers is formed in substrate **402** on wafer **430**, including doped n -regions **406** (N^+) and **408** (N^- to N), and doped p -regions **410** (P to P^+) and **412** (P^-). As indicated, region **406** is strongly doped, regions **408** and **410** have different subregions with different doping concentrations, and region **412** is normally doped. Region **408** includes a buried layer **432** (N^+) more strongly doped than adjacent regions. Regions **410** and **412** respectively include contact regions **438** (P^{++}) more strongly doped than adjacent regions. An insulation layer **422**, which can be made of SiO_2 , is formed on top of the doped layers. Layer **422** has a portion **442** with reduced thickness at a window area **444**. Conductors **420** respectively extend from the doped layers through insulation layer **422** for electrical interconnect. Each of regions **406**, **408**, **410**, and **412** is in electrical communication with two contactors **420**. Conductors **420** can be made of metal.

[0062] Again, a protective cover and/or other electronic structures (not shown) may be formed on substrate **402**.

[0063] The layers and regions may have the exemplary doping concentrations and thicknesses list in **Table I**.

TABLE I.

Region or layer		Doping concentration (cm^{-3})	Thickness (microns)
406		1E19	0.04
408	Top portion	1.5E15	2.5
	Middle portion	1.5E17	0.5
	432	1E19	1

410	Top portion	3E16	0.5
	Bottom portion	1E18	0.15
412		1E14 ... 1E16	10 to 20
430		1E18	(standard wafer thickness)

[0064] As mentioned above, regions **408** and **410** each has different sub-regions with different doping concentrations. The more strongly doped lower portion in each region can limit undesirable extension of the depletion region developed from the *pn*-junction below and allow increased conductivity within the lower half for more effective collection of photogenerated carriers.

[0065] Cell **400** can be similarly fabricated as cell **100**, **200**, or **300** with some modifications that will be apparent to persons skilled in the art. In particular, doped layers may be epitaxially grown and then etched (such as by dry etching) to form regions **406**, **408**, **410** and **432**, so that a portion of each layer is exposed. Contact regions **438** may be formed by diffusion or implantation. It may be convenient to form all contact regions **438** in a single implantation/drive-in sequence. A SiO₂ layer **422** can be deposited on top of regions **406**, **410**, **412** and **432** after they have been formed. Layer **422** can be planarized using a suitable planarization technique such as CMP. The thick portions of layer **422** may be formed of field oxide (FOX) while thin portion **442** may be formed of MOS gate oxide. Thin portion **442** may be about 100 Å thick. Layer **422** can be etched to form window area **444**. Openings in layer **422** can be made and conductors **424** can be placed on each one of regions **406**, **410**, **412** and **432** through the openings with a suitable metallization technique. Contact regions **438** may be formed before forming layer **422** or after etching the openings.

[0066] A protective cover (not shown) may be formed on layer **422** in a suitable manner, as discussed above.

[0067] FIG. 5 illustrates a possible cell **500**, a variation of cell **400**. The difference between cell **500** and cell **400** is that the region **502** below the bottom *pn*-junction **504** is

isolated by isolation trenches 506 and SiO₂ insulating layer 508. Cell 500 may be formed on a silicon-on-insulator (SOI) wafer, which has layer 508 and a semiconductor layer 510. Thus, each trench 506 extends between insulation layers 508 and 522 for laterally isolating regions on its opposite sides from each other. Trenches 506 may be formed before buried layers 512 and contact regions 514 have been formed by diffusion. As can be appreciated, when region 502 is formed on top of a SOI wafer, region 502 can have a very different doping concentration or different doping type than that of layer 510. Layer 510 can be weakly, normally, or strongly doped, while region 502 can still have a doping concentration within a wide range, including one that is much different from that of region 412 in cell 400. For example, region 502 may include a thin but very strongly doped bottom sub-region and a much thicker but very weakly doped sub-region above it.

[0068] Cells 500 can form pixels in a photo-sensing device with good electrical insulation between neighboring pixels.

[0069] FIG. 6 illustrates another possible variation of cell 400. A difference between cell 600 and cell 400 is that the contact 602 for the bottom *p*-type region 604 is below and in contact with the contact region 606 below region 604. Contact region 606 is strongly doped. Consequently, a buried layer 608 can extend over the full width of cell 600 and the number of contact regions formed by diffusion and the number of openings in the top insulation layer can be reduced. Cell 600 may be advantageous. It may be easier to fabricate. In some applications, it may be permissible or desirable that electrical contact be made from the backside (i.e. the bottom side in FIG. 6) of the photo-sensing cell. For example, as can be seen by comparing FIGS. 4 and 6, the lateral size of cell 600 may be reduced in comparison to cell 400 because fewer contacts are required at the front side.

[0070] As can be understood, the exemplary embodiments described herein may be modified. For example, the number of vertically-stacked *pn*-junctions may be increased. The doping types of the layers or regions in a photo-sensing cell may be reversed. The operation of such a reversed cell is similar to the operation of the original cell, except that all polarities, biasing voltages or current directions may also be reversed.

[0071] Each of the photo-sensing cells described herein can be used either alone or in

an array of cells. In an array of cells, the cells may be advantageously isolated from each other by the isolation regions such as isolation trenches or insulation layers.

[0072] Other features, benefits and advantages of the embodiments described herein not expressly mentioned above can be understood from this description and the drawings by those skilled in the art.

[0073] Of course, the above described embodiments are intended to be illustrative only and in no way limiting. The described embodiments are susceptible to many modifications of form, arrangement of parts, details and order of operation. The invention, rather, is intended to encompass all such modification within its scope, as defined by the claims.

WHAT IS CLAIMED IS:

1. A photo-sensing cell comprising:
 - a substrate having a surface;
 - a plurality of regions formed in said substrate beneath said surface one below another and alternatively doped of first and second conductive types, thus forming a plurality of *pn*-junctions at different depths relative to said surface, said depths chosen for detection of light of respective wavelength bands incident on said surface;
 - a conductive region formed in said substrate extending from said surface to an associated one of said plurality of regions; and
 - one or more insulation regions formed in said substrate, each extending from said surface proximate and along said conductive region for laterally isolating said conductive region from an adjacent depletion region.
2. The photo-sensing cell of claim 1, further comprising electrical interconnects in electrical communication with said plurality of regions for detecting electrical signals respectively derived from depletion regions developed from said *pn*-junctions so that incident light on said surface through said electrical interconnects.
3. The photo-sensing cell of any one of claims 1 to 2, wherein at least one of said insulation regions comprises an etched trench filled with an insulation material.
4. The photo-sensing cell of claim 3, wherein said insulation material comprises at least one of SiO₂ and undoped polysilicon.
5. The photo-sensing cell of any one of claims 1 to 4, wherein said conductive region is more strongly doped than its associated region with a same conductive type.
6. The photo-sensing cell of any one of claims 1 to 5, wherein said plurality of regions comprises a first region and an adjoining second region epitaxially formed on said first region.

7. The photo-sensing cell of claim 6, wherein said second region comprises a sub-region adjoining said first region, said sub-region more strongly doped than its adjacent regions to limit expansion of a depletion region within said sub-region and to form an electrical path in said sub-region having a lower resistivity than those of said adjacent regions.
8. The photo-sensing cell of claim 6 or claim 7, further comprising a wafer on which said first region is formed.
9. The photo-sensing cell of any one of claims 1 to 8, wherein one or more of said plurality of regions each comprises one or more contact sub-regions extending from said surface, each one of said contact sub-regions more strongly doped than its adjacent regions for interconnection with an electrical interconnect.
10. A photo-sensing cell comprising:
 - a plurality of semiconductor layers, formed epitaxially one on top of another;
 - an insulation layer having a surface, formed on said semiconductor layers;
 - said semiconductor layers alternately doped of first and second conductive types, thus forming a plurality of *pn*-junctions at different depths relative to said surface of said insulation layer, said depths selected for detection of light of respective predetermined wavelength bands incident on said surface;
 - a plurality of conductors, each extending from one of said layers through said insulation layer for interconnection with an electrical interconnect.
11. The photo-sensing cell of claim 10, wherein said insulation layer comprises SiO₂.
12. The photo-sensing cell of claim 10 or 11, wherein a first one of said semiconductor layers comprises a region adjoining a second one of said semiconductor layers, said region more strongly doped than its adjacent regions to limit expansion of a depletion region within said first layer and to form an electrical path in said region having a lower resistivity than those of said adjacent regions.

13. The photo-sensing cell of any one of claims 10 to 12, wherein one or more of said conductor layers comprise one or more contact regions, each one of said contact regions more strongly doped than its adjacent regions and adjoining one of said conductors.
14. The photo-sensing cell of any one of claims 10 to 13, further comprising a wafer on which said plurality of semiconductor layers is formed.
15. The photo-sensing cell of claim 14, wherein said wafer comprises a semiconductor layer more strongly doped of a conductive type same as the adjoining one of said plurality of semiconductor layers.
16. The photo-sensing cell of claim 14 or claim 15, further comprising a conductor attached to said semiconductor layer of said wafer for interconnection to an electrical interconnect.
17. The photo-sensing cell of claim 14, wherein said wafer comprises a silicon layer and an insulation layer adjoining said silicon layer, said plurality of semiconductor layers formed on said insulation layer of said wafer.
18. The photo-sensing cell of claim 17, further comprising one or more isolation trenches each extending between said insulation layers for isolating semiconductor regions on opposite sides of said each isolation trench from each other.
19. The photo-sensing cell of any one of claims 1 to 18, wherein said plurality of *pn*-junctions comprises three *pn*-junctions for detection of three color components of light incident on said surface.
20. A semiconductor device comprising one or more photo-sensing cells each according to any one of claims 1 to 19, at least two adjacent ones of said photo-sensing cells electrically isolated from each other by an insulation region.
21. A method of forming a semiconductor device, comprising:

epitaxially growing on a wafer a plurality of layers one on top another and alternatively doped of first and second conductive types, thus forming a plurality of *pn*-junctions;

exposing a portion of each one of at least two of said plurality of layers;

forming an insulation layer on said exposed portions, said insulation layer having a surface, the depths of said *pn*-junctions relative to said surface respectively chosen for detection of light of different wavelength bands incident on said surface; and

placing a conductor on each one of said exposed portions, said conductor extending from said exposed portions through said insulation layer.

22. A method of forming a semiconductor device, comprising:

epitaxially growing, on a first layer of a first conductive type, a second layer of an opposite, second conductive type, thus forming a first *pn*-junction;

forming, in said second layer, a first well region doped of said first conductive type, thus forming a second *pn*-junction;

forming, in said first well region, a second well region doped of said second conductive type, thus forming a third *pn*-junction, said *pn*-junctions at respective depths, relative to a surface of said second layer, chosen for detection of light of different wavelength bands incident on said surface;

forming, in said second layer and away from said first well region, a conductive region doped of said first conductive type extending from said first layer through said second layer; and

forming an isolation trench in said second layer proximate and along said conductive region for isolating said conductive region from a depletion region within in said second layer.