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(54) **BACKSIDE NANOSCALE TEXTURING TO IMPROVE IR RESPONSE OF SILICON SOLAR CELLS AND PHOTODETECTORS**

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(57) **ABSTRACT**
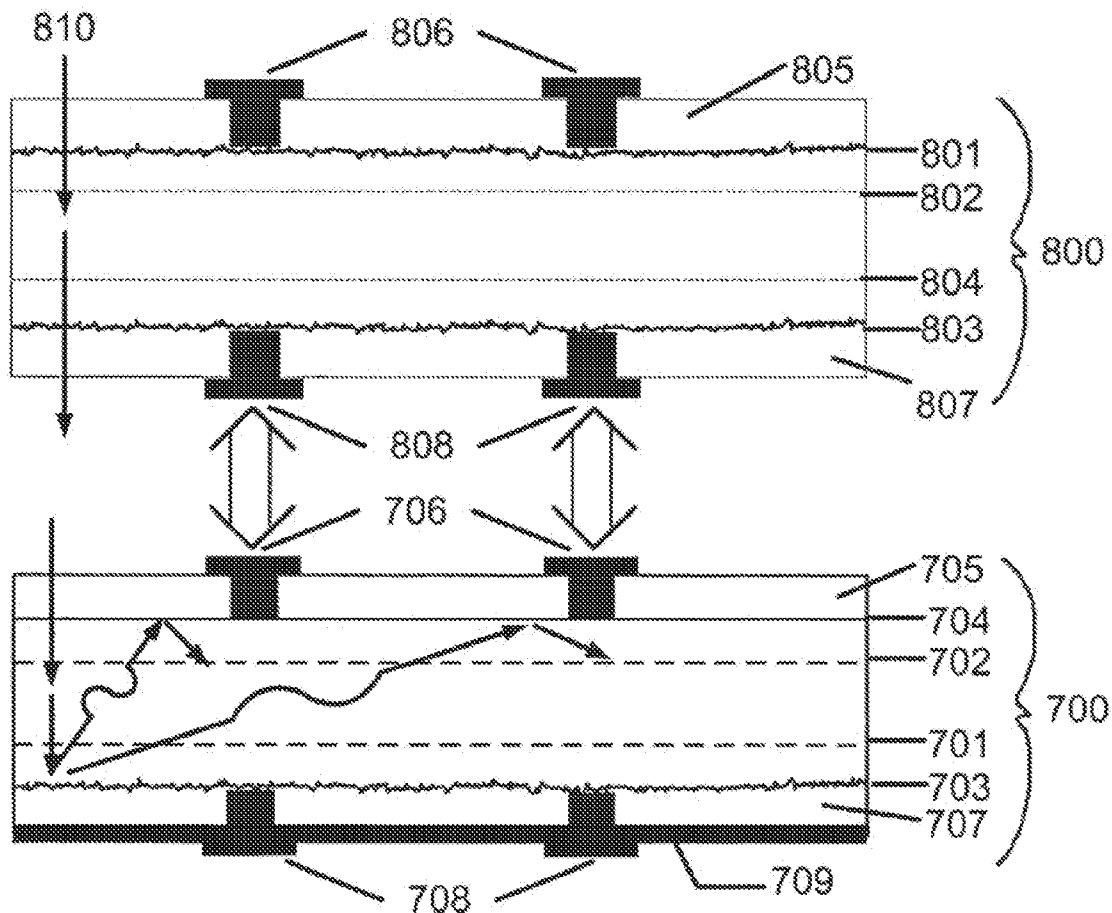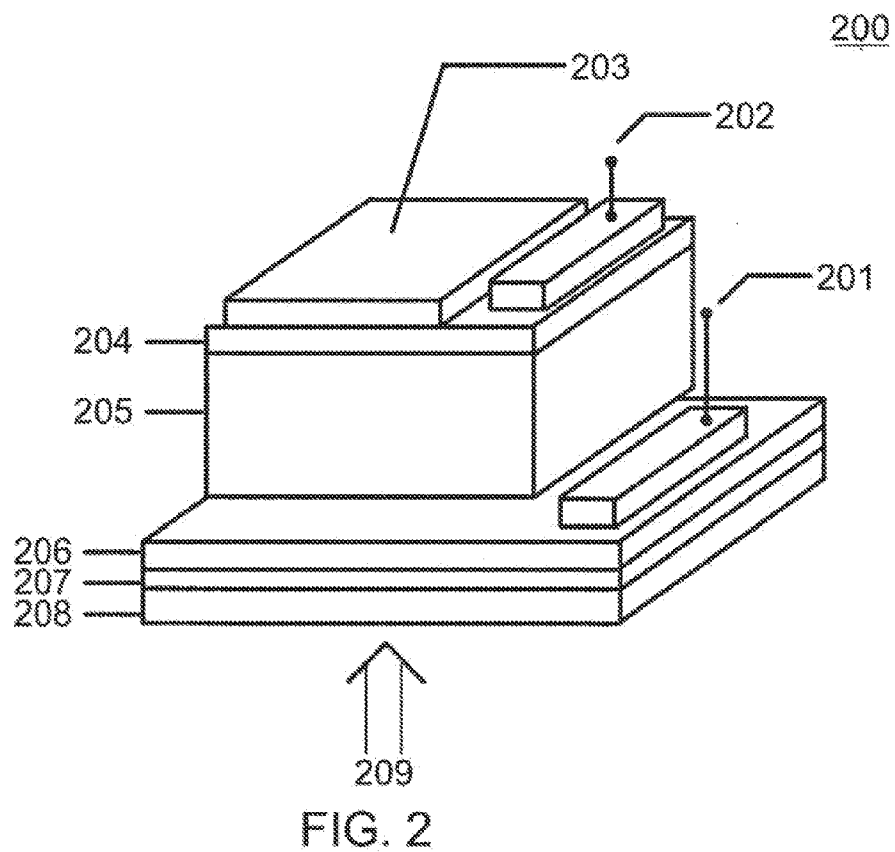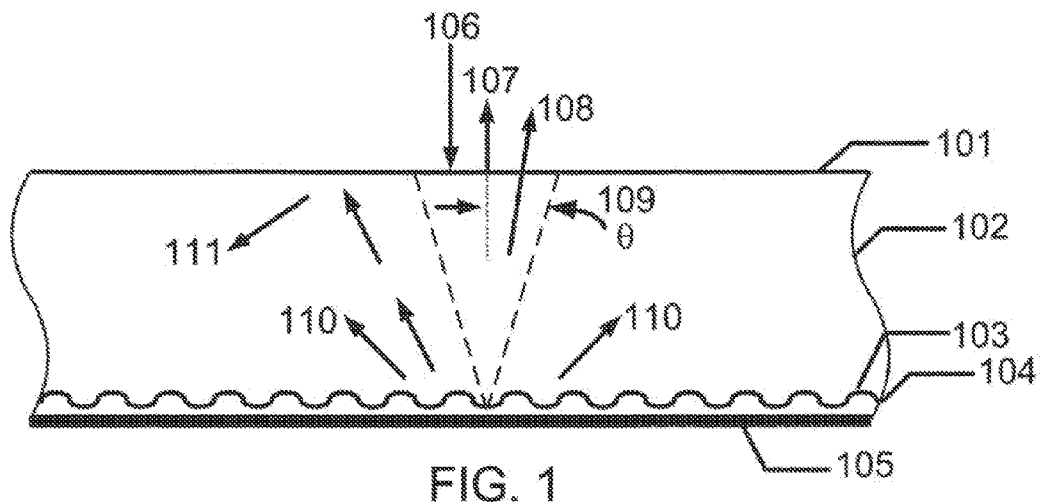
The absorption coefficient of silicon for infrared light is very low and most solar cells absorb very little of the infrared light energy in sunlight. Very thick cells of crystalline silicon can be used to increase the absorption of infrared light energy but the cost of thick crystalline cells is prohibitive. The present invention relates to the use of less expensive microcrystalline silicon solar cells and the use of backside texturing with diffusive scattering to give a very large increase in the absorption of infrared light. Backside texturing with diffusive scattering and with a smooth front surface of the solar cell results in multiple internal reflections, light trapping, and a large enhancement of the absorption of infrared solar energy.

106
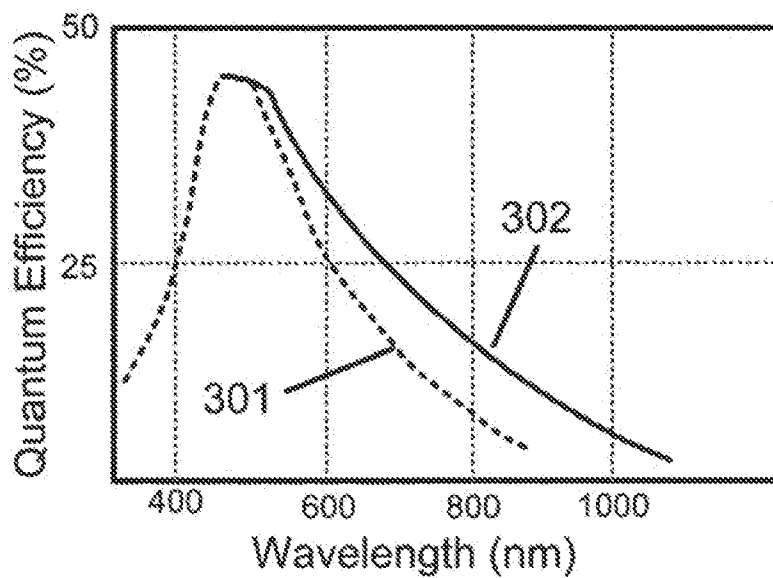107
108
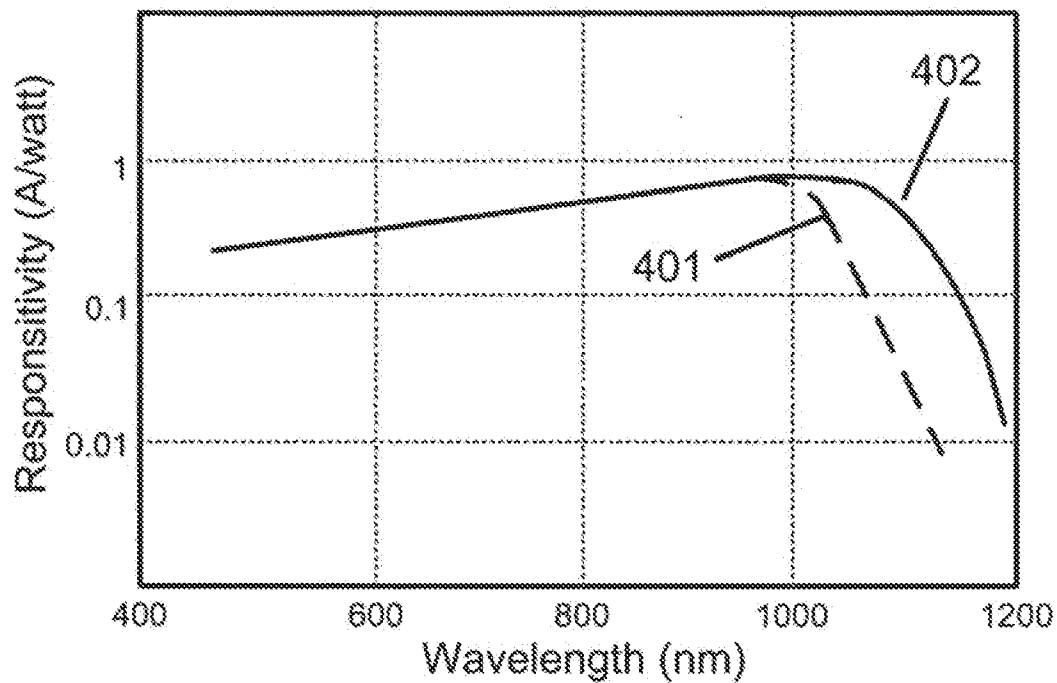101
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FIG. 1

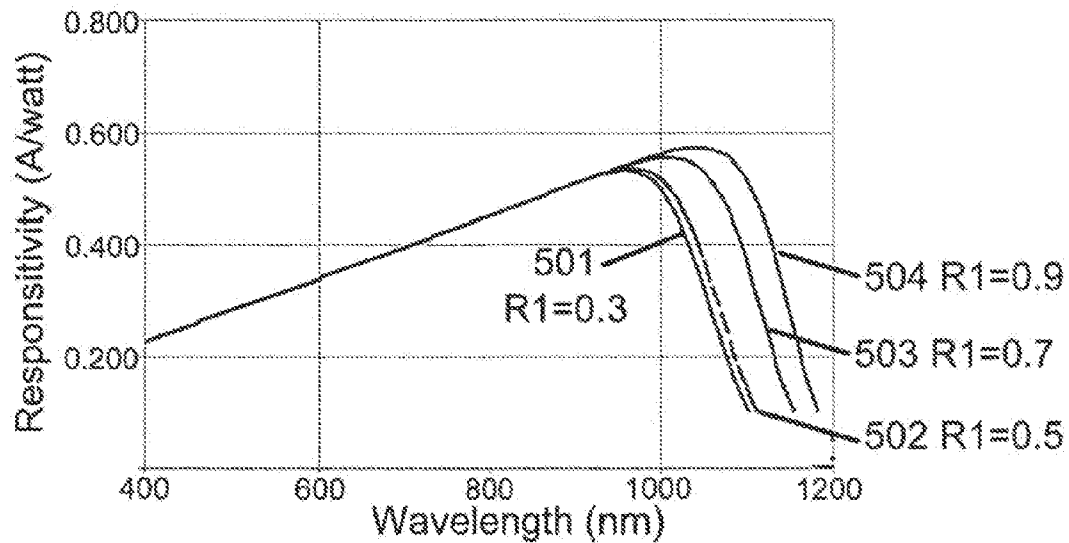200
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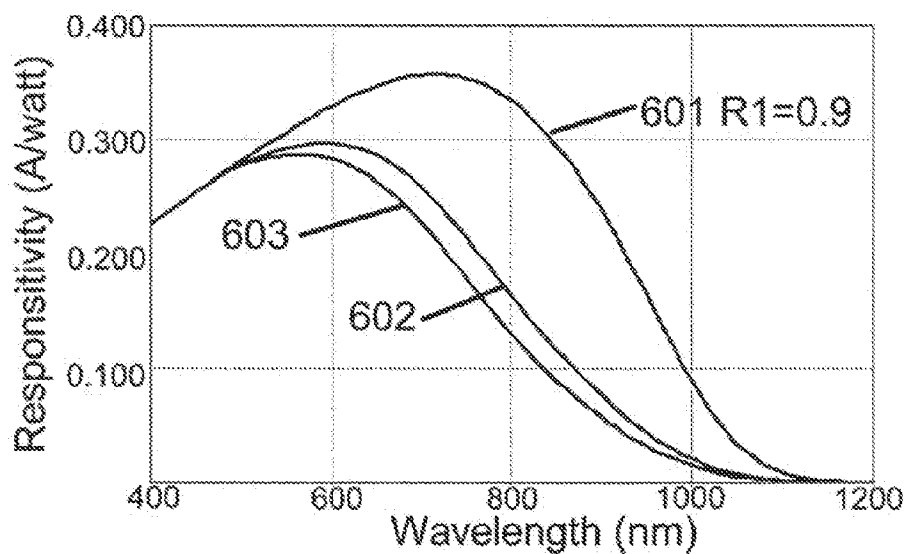205
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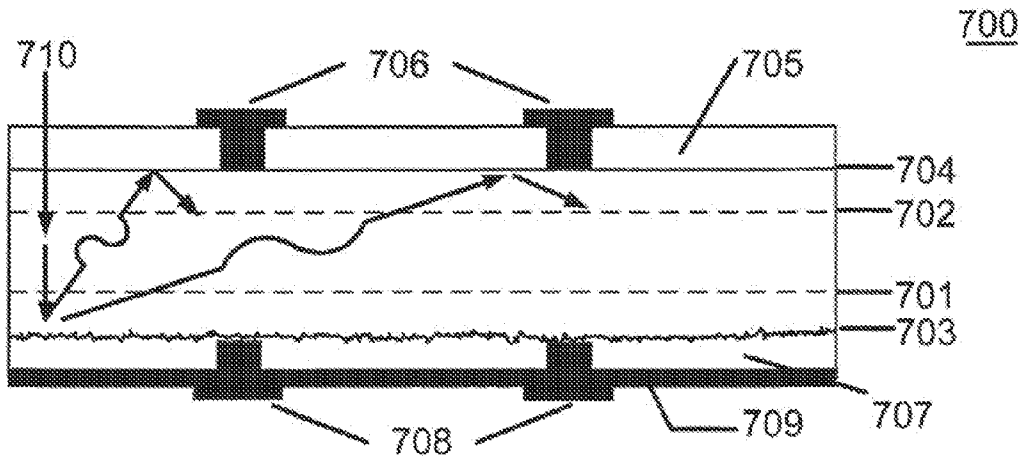207
208
209

FIG. 2

FIG. 3

FIG.4

FIG. 5

FIG. 6

FIG. 7
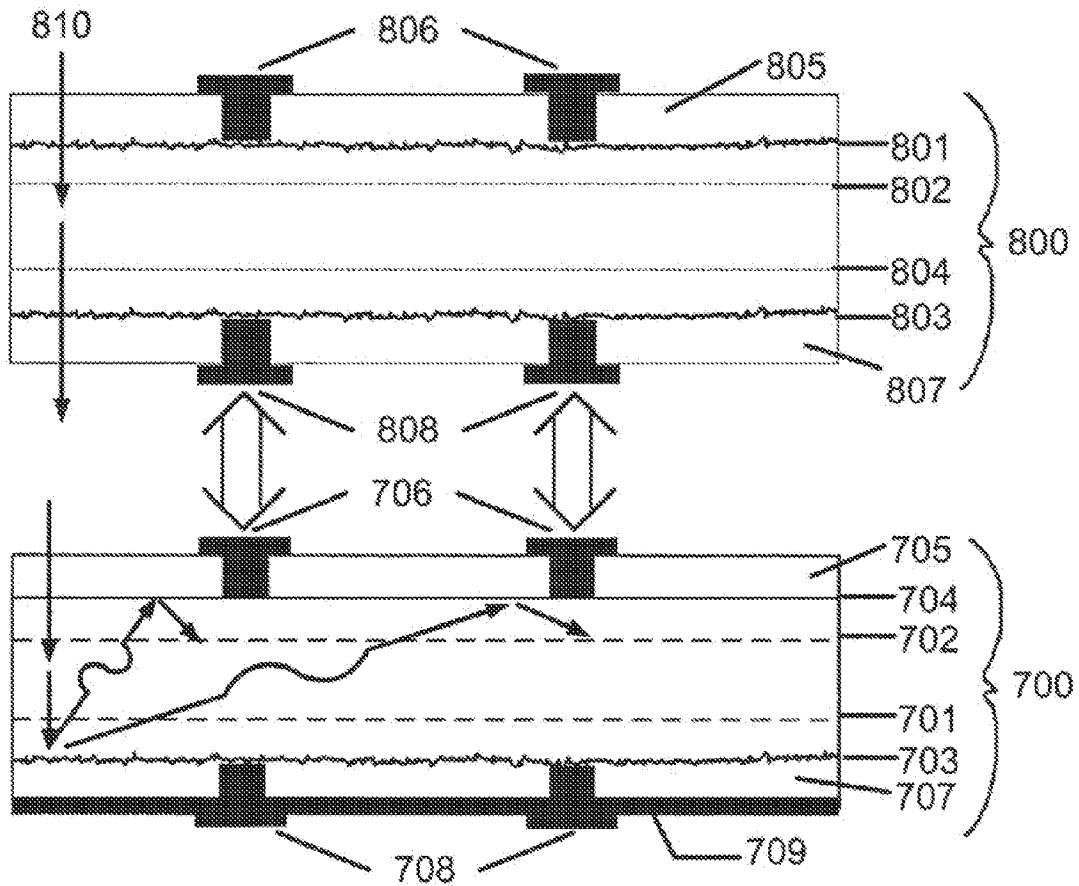
FIG. 8

BACKSIDE NANOSCALE TEXTURING TO IMPROVE IR RESPONSE OF SILICON SOLAR CELLS AND PHOTODETECTORS

[0001] This application is a continuation of U.S. patent application Ser. No. 13/373,074, filed on Nov. 3, 2011, which is a continuation of U.S. patent application Ser. No. 12/927, 423, filed on Nov. 15, 2010, which claims the benefit of U.S. Provisional Patent Application No. 61/285,416, filed on 10 Dec. 2009.

TECHNICAL FIELD

[0002] The present invention relates to silicon solar cells with improved energy conversion efficiency. More specifically, the present invention relates to backside textured silicon solar cells with diffusive backside scattering and reflection of the incident red and infrared light reaching the backside.

BACKGROUND

[0003] Texturing has been used as a technique for light trapping and to improve the efficiency of photodetectors and solar cells due to multiple internal reflections and light trapping. A portion of the known literature describes the use of backside texturing of photodiodes to improve the absorption of near infrared light energy. One of the first descriptions of using this technique in photodetectors was by A. E. St. John in U.S. Pat. No. 3,487,223, "Multiple Internal Reflection Structure in a Silicon Detector which is Obtained by Sandblasting". Another description was provided by J. E. Cotter, "Optical intensity of light in layers of silicon with rear diffuse reflectors," Journal of Applied Physics, vol. 84, no. 1, pp. 618-24, 1 Jul. 1998. A more recent description of the same technique on ultra-thin solar cells has been given by O. Berger, D. Inns and A. G. Aberle, "Commercial white paint as back surface reflector for thin-film solar cells," Solar Energy Materials & Solar Cells, vol. 91, pp. 1215-4221, 2007, hereinafter referred to as Aberle. Aberle disclosed the use of white paint as the backside diffuse reflector. Aberle's initial results show a large increase in the absorption with the white paint as a back surface reflector but only a modest ten or twenty percent increase in the quantum efficiency. Aberle's later results indicate that a twenty to forty percent enhancement in conversion efficiency can be obtained on thin film microcrystalline solar cells by adding more titanium dioxide to the white paint. However, thick layers of the order 80 μm or more of paint are required on thin film solar cells which in themselves are only a few micrometers thick.

[0004] A very recent analysis of the enhancement of infrared absorption in solar cells and photo detectors has been disclosed by L. Forbes and M. Y. Louie, "Backside Nanoscale Texturing to Improve IR Response of Silicon Photodetectors and Solar Nanotech, vol. 2, pp. 9-12, June 2010. Regularly textured surfaces have been described for solar cells, by A. Arndt, J. F. Allison, J. G. Haynos, and A. Meulenberg, "Optical properties of the COMSAT non-reflective cell," 11th IEEE Photovoltaic Spec. Conf., p. 40, 1975. The majority of solar cells use single front side textured surfaces. Front side texturing serves to reduce the reflectivity of the silicon surface due to multiple attempts at transmission through the front surface as has been described by A. Arndt. U.S. Pat. No. 5,589,704 to Levine, "Article Comprising a Si-based Photodetector," describes the front side texturing of a photodetector by plasma etching. Surface texturing of the illuminated side of solar cells, in the form of a regular, saw-tooth pattern has

also been described in U.S. Pat. No. 5,641,362 to Meier, "Structure and Fabrication Process for an Aluminum Alloy Junction Self-aligned Back Contact Silicon Solar Cell". Further, U.S. Pat. No. 7,582,515, to Choi et al. "Multi-Junction Solar Cells and Methods and Apparatus for Forming Same" discloses a tandem configuration, which is a single piece of semiconducting material. A tandem arrangement as described herein means a single substrate of semiconductor material in which processing has created various layers having individual characteristics of optical, electrical, and/or mechanical properties. U.S. Pat. No. 5,627,081 to Tsuo, et al., describes porous silicon structures on the front side of substrates to reduce reflectance of visible light, U.S. Pat. No. 4,673,770 to Mandelkorn "Glass sealed silicon membrane solar cell" describes aground and silvered bottom glass cover plate separated from the substrate but not structures etched into or deposited on to the substrate. U.S. Pat. No. 5,080,725 to Green, et al., "Optical properties of solar cells using tilted geometrical features," describes ridges and pyramids etched into the substrate producing reflections only at specific angles. Matsuyama et al., in U.S. Pat. No. 6,072,117, to Matsuyama et al. "Photovoltaic Device Provided with an Opaque Substrate Having a Specific Irregular Surface Structure", disclose solar cells CVD deposited upon opaque substrates with linear recesses.

[0005] From the foregoing it is apparent that there are conflicting requirements for the absorption of infrared light energy and visible light energy. Front side texturing is desirable to maximize absorption of visible light energy and the backside condition is irrelevant since visible radiation is strongly absorbed and utilized near the front surface. On the other hand, a smooth front side and textured backside is desirable to maximize the utilization of infrared light energy.

[0006] Front side textured anti-reflecting layers, or antireflecting layers on top of front side texturing are required to maximize absorption of visible light energy, the backside condition is irrelevant since visible radiation is strongly absorbed near the front surface. On the other hand a smooth front side and textured backside is needed to maximize the utilization of infrared light energy. Front side anti-reflecting layers that transmit visible radiation can be used in conjunction with backside diffusive texturing since these front side layers will be reflecting in the infrared.

SUMMARY

[0007] Accordingly, a semiconductor solar cell or photodetector having improved incident radiation absorption is disclosed, in which a silicon substrate has a substantially planar first surface available to the incident radiation and a layer transparent to visible light and infrared wavelengths is disposed at the first surface. This layer is internally reflective to infrared wavelengths of radiation scattered within the first semiconductor substrate. A textured layer is disposed at a second surface of the silicon substrate, the textured layer being a diffusive radiation scattering layer for infrared wavelengths of radiation, and a reflecting layer disposed on the textured layer and spaced apart from the second surface by the textured layer, whereby infrared wavelengths of radiation are returned through the textured layer toward the first semiconductor substrate.

[0008] Another substrate substantially transparent to infrared incident radiation may be stacked with the silicon substrate in a manner leaving a gap between the two substrates, such that a difference between the index of refraction of a

substrate and the gap results in infrared wavelength energy internally scattered is reflected back into the latter silicon substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a fuller understanding of the nature and advantage of the present invention, reference is being made to the following detailed description of preferred embodiments and in connection with the accompanying drawings, in which:

[0010] FIG. 1 is an illustration of a solar cell or photodetector cross section in which scattered backside total reflection from a regularly textured backside and backside mirror-like reflector.

[0011] FIG. 2 is an illustration of a thin film microcrystalline solar cell.

[0012] FIG. 3 is a graph of external quantum efficiency versus incident energy wavelength for a solar cell/photodetector with diffuse back surface reflector or Pigmented Diffuse Reflector (PDR), white paint, and without a diffusive backside reflector.

[0013] FIG. 4 is a graph of improvement in the infrared responsivity of a silicon solar cell/photodetector employing backside texturing and a backside mirror-like reflector.

[0014] FIG. 5 is a graph of responsivity of a 200 μm thick crystalline solar cell with planar front surface and with different amounts of diffusive scattering at the back surface.

[0015] FIG. 6 is a graph of responsivity of a thin microcrystalline solar cell with different amounts of diffusive scattering at the back surface.

[0016] FIG. 7 is a cross sectional illustration of a thin film microcrystalline silicon solar cell/photodetector which may employ the present invention.

[0017] FIG. 8 is a cross sectional illustration of stacked solar cells/photodetectors fir absorption of visible light in the top cell and absorption of infrared light in the bottom cell and which may employ the present invention.

DETAILED DESCRIPTION

[0018] The conflicting requirements for optimal absorption of both infrared and visible light energy are resolved as described in the following disclosure. Various techniques have been previously described for the texturing of silicon solar cells. The present disclosure relates to irregularly textured silicon technology based solar cells and photodetectors by nanometer- and micrometer-sized structures that produce a true diffuse scattering of desirable wavelengths of incident radiation. While silicon is the preferred semiconductor base material, other elemental and compound semiconductors such as Ge, GaAs, CdTe, CuInGaSe, and others exhibiting a photoelectric effect may also benefit from the use of the present invention. Diffuse scattering or diffuse reflection is an important concept and, as used herein (and compatible with a definition available from Wikipedia.org), is intended to mean the scattering or reflection of light from a surface such that an incident ray is reflected at many angles that can be described as arbitrary, rather than at just one precise angle, which is the case of specular reflection. If a surface is completely non-specular, the reflected light will be evenly scattered over the hemisphere surrounding the surface. Materials can reflect diffusely if their surface is randomly rough on the microscopical scale of the radiation being scattered or reflected.

[0019] Solar cells and photodetectors are typically comprised of diodes formed in a semiconducting material. The solar cell/photodiode disclosed herein includes a semiconductor bulk substrate with at least one photoelectric conversion diode layer disposed in the substrate and at least one light anti-reflecting region formed in or optically near the semiconductor substrate surface on which the radiation is initially incident. Such incident radiation is expected to occur at a range angles relative to the plane of the top surface of the semiconductor substrate, including normal to the top surface, and this radiation is considered to be available to the solar cell/photodiode. The light anti-reflecting region includes an air-substrate index of refraction matching layer and, in some embodiments, light diffusing layer with features configured to increase the effective absorption efficiency and energy conversion efficiency of the solar cell/photodetector. The anti-reflecting features may be cones, pyramids, pillars, protrusions and other like features, and, when such features are used for diffusion, are distributed in a random fashion. It should be noted that any feature that produces the desired diffusive light scattering is one that closely approximates a Lambertian scattering surface at the desired wavelengths of radiation. Lambertian scattering is ideal diffuse scattering providing light distributed over the whole half sphere or solid angle of 2π sterradians. Manipulating the feature sizes, dimensions, etc. allows the light anti-reflecting and light diffusing region to be tunable for a specific wavelength. Varying the material near or deposited upon the anti-reflecting and light diffusing region can also be used to enhance these characteristics.

[0020] An embodiment of the solar cell disclosed herein includes a semiconductor bulk substrate substrate with at least one photoelectric conversion diode layer disposed in the substrate and at least one light diffusing region formed in or optically near the semiconductor substrate surface on which the radiation is initially incident, and a reflector behind the light diffusing region. The light diffusing features, as discussed above, are chosen from cones, pyramids, pillars, protrusions and other like features, and combinations thereof. These features also closely approximates a Lambertian light scattering surface.

[0021] The light diffusing regions are formed by methods known to those skilled in the art to produce micrometer or smaller features on or within substrates of semiconductor material. These may be formed before, during or alter the formation of solar cells/photodetectors and are formed on semiconductor substrates that are considered "thick", e.g., having a range of thickness between 500 μm and 5 μm, such as may be the result of the sawing process of a semiconductor ingot. Or, are formed on semiconductor substrates that are considered "thin", e.g., having a range of thickness between 10 μm and 1 μm, such as may be the result of a deposition process yielding microcrystalline silicon or amorphous silicon or both. As employed in the present disclosure, the following terms have the following meanings, compatible with those found at wikipedia.org. Crystalline, or single crystal, silicon is silicon in which the crystal lattice of the entire sample is continuous and unbroken with no grain boundaries. Multicrystalline silicon is a silicon sample in which segments of the silicon are composed of large crystals that may have different orientations with grain boundaries between the crystals. When out into substrates several different crystals may be visible to the eye. Polycrystalline materials are made of a three dimensional mosaic of small, irregularly shaped crystals. Microcrystalline silicon is a form of silicon having a paracrystalline structure; paracrystalline materials have only

short and medium range ordering in their lattice structures over micrometer dimensions. Amorphous silicon has no crystal structure and is disordered, or the atoms are arranged in no particular order.

[0022] Traditional solar cells, photodiodes, and photodetectors, designated in FIG. 1, use what is called FSI, or Front Side Illumination technology, where the radiant energy 106 is incident on a planar surface 101 of an absorbing silicon substrate 102. In conventional CMOS imagers employing a photodetector, the substrates 102 are hundreds of micrometers thick but epitaxial or silicon-on-insulator substrates arc used to limit the depth of absorption of the incident radiation and CMOS and CCD imagers are sometimes thinned to a few micrometers. Recently solar cells have been fabricated using thin films of microcrystalline silicon. As a result of the thin active film thickness of these devices, the efficiency of the absorption of infrared and long wavelength visible light in thin silicon films has become important.

[0023] When the silicon is not strongly absorbing in the near infrared a back side textured surface works in conjunction with a totally internally reflecting front side surface to best increase the absorption of near infrared photons. This results in multiple internal reflections and light trapping.

[0024] An embodiment described herein for visible light, infrared, and near infrared, NIR, detectors and imagers and thin film solar cells front side illumination and backside texturing. The backside texturing is particularly designed to provide true diffusive scattering and, in one alternative embodiment has a transparent conductive oxide treated or patterned to produce randomly positioned or otherwise arranged for a scattering property yielding a Lambertian scattering of energy of a selected band of wavelengths and a reflecting layer preferably formed of a metallic material.

[0025] Consider now the effect of texturing on the near infrared wavelength response; texturing will also change the absorption in the remaining part of the visible light region but this will not be considered here. A typical semiconductor substrate 102 is shown in cross section in FIG. 1. The back surface 103, i.e., the surface opposite the top surface 101, is coated with a conductive oxide layer 104 that is regularly textured with grooves or ridges or similar patterns to produce an internal reflection that is not specular. In the near infrared the index of refraction of silicon is η=3.42 and the reflectance is about R=30% from a single surface and transmittance through a single surface is T=70% for normal incident waves. The absorption coefficient of silicon is very low in the near infrared. In FIG. 1 radiation under normal incidence, represented by arrow 106, is reflected from the first surface 101, and this is shown as arrow 107. There are successive reflections from both the back, represented by arrows 108 and 110, and internal reflections from the front surface, arrow 111, resulting in a total transmittance, if there is no reflective metal layer 105 disposed on the oxide layer 104, of

$$T_{tot} = (T\,T)(1+R^2+R^4+\dots) = (T\,T)/(1-R^2) \qquad (1)$$

[0026] This result has been obtained using the sum of a geometric series. If both top and back surfaces are just polished silicon-air then this results in a total transmittance of 54% and a reflectance of 46%.

[0027] If the increase in the individual path lengths caused by the diffuse scattering is neglected and if the absorption coefficient is very low then the total effective path length is determined by just the number of reflections, and the total absorption can be shown to be

$$A = \alpha d(1+R_2)(1+R_1R_2+R_1{}^2R_2{}^2+\dots) = \alpha d(1+R_2)/(1-R_1R_2) \qquad (2)$$

Here, α, is the absorption coefficient in reciprocal cm and, d, is the thickness of the sample in cm, and the effective increase in path length is Enh=$(1+R_2)/(1-R_1R_2)$. The internal quantum efficiency, IQE, in the infrared where the absorption in silicon is low is then, IQE=αd Enh. The external quantum efficiency, EQE, is EQE=T_1IQE and EQE=T_1 αd Enh.

[0028] If both sides of an infrared photo detector or thin film silicon solar cell are polished then T_1=T_2=0.70 and R_1=R_2=0.3 which gives Enh=1.4, IQE=1.4 αd and EQE=αd.

[0029] An embodiment that improves the infrared response has the top side 101 polished but the back side 103 textured with an oxide 104 like silicon oxide or transparent conductive oxides 104 like zinc oxide, indium oxide, or tin oxide, and a metal like aluminum or silver or mirror reflector 105 behind. The texturing is realized in a fashion to produce a true diffuse scattering, a Lambertian scattering, at the infrared wavelengths. This diffuse scattering layer/reflecting layer combination, in essence, yields an R_2=100%, a diffuse reflector. The reflectance of the polished front side to the scattered light radiation is determined by solid angle considerations. Any incident light with an angle of incidence greater than the critical angle θ, 109, will be totally internal reflected, 111. If the backside scattering is totally diffuse or Lambertian, the transmittance is then determined by the area of the surface, πr.sup.2, within the critical angle θ, 109, in this case 17° for silicon and air. The radius of the circle is r=d sin(17), where, d, is the thickness of the sample. This area is divided by the area of the half sphere, $2\pi d^2$. If the backside scattering is totally diffuse the transmittance of the front planar surface is then roughly T_1=3% and the reflectance R_1=97%. The path length enhancement factor can be very large

$$Enh = (1+R_2)/(1-R_1R_2) = 66 \qquad (3)$$

[0030] This would result in an IQE=66 αd and an EQE=46, this is consistent with Cotter's estimate defined as, $4\eta^2$, where, η, is the optical index of refraction of the semiconductor, then for a backside textured silicon photodetector $4\eta^2$=51 in the near infrared where the index of refraction for silicon η=3.42. If the backside is a textured and truly diffusive scattering surface and a mirror like surface is used behind the back side, aver large enhancement of absorption in the near infrared can be achieved.

[0031] Aberle has described a related technique for thin solar cells. As an aid to understanding, FIG. 2 reproduces an isometric view of Aberle's thin solar cell 200 with front side and backside electrical contacts 201 and 202, respectively. Aberle used white paint as the backside reflector. Aberle's initial results show a large increase in the absorption by the solar cell with the white paint as a back surface reflector but only a modest ten or twenty percent increase in the quantum efficiency, as shown herein in FIG. 3. These thin films are deposited on a glass plate, 208, covered with silicon nitride, 207. A seed layer, 206, is used to form the microcrystalline absorbing layer, 205. Layer, 204, is a heavily doped junction forming layer and 203 is a back surface reflector. Layer 203 is thick only in Aberle's case, in FIG. 2 it is shown as a thin metal reflector.

[0032] As shown in FIG. 3 the quantum efficiency, curve where a pigmented backside reflector, e.g. white paint, is used can be compared to a back surface without the pigmented back side. They indicate that a twenty to forty percent enhancement in conversion efficiency can be obtained on thin film micro-

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crystalline solar cells by adding more titanium dioxide to the white paint. However, thick layers of the order 80 micrometers or more of paint are required on thin film solar cells **200** which in themselves are only a few micrometers thick.

[0033] FIG. **4** shows the improvement realized with one embodiment of the present invention on thick silicon samples for a backside textured Lambertian scattering surface in the near infrared. The normal or conventional results for a single pass of a 100 μm thick epitaxial sample curve **401** are compared to backside texturing with total internal reflections at the front side and light trapping in curve **402**. "Light trapping" means that the light is confined by internal reflections in the semiconductor layer until it is absorbed. The enhancement factor observed at infrared wavelengths like 1100 nm is at least a factor of twenty. The 100 μm backside textured sample, curve **402**, appears like a 700 μm sample with no texturing that is measured also as curve **402**. A comparison is being made between the thinner 100 μm sample and a thick 700 μm sample. Multiple internal reflections without texturing but with an ideal metal backside reflector results in an enhancement factor from Eqn. 3 of about three. The 700 μm thick sample with no texturing, curve **402**, but a backside metal reflector will then have an apparent of effective thickness of 2000 μm. A 100 μm sample could ideally have an enhancement of over 60 but in the practice this is limited by non-ideal losses so than the actual enhancement is around twenty and both samples have an apparent thickness of 2000 μm. This results in a useful absorption in silicon out to 1100 μm or the indirect bandgap energy of silicon.

[0034] If the absorption in the silicon layer is not assumed to be small but rather taken into account it can be shown that the enhancement factor for the internal quantum efficiency due to multiple reflections is modified from Eqn. 3 and becomes

$$Enh = (-1 \exp(-\alpha d))(1 + R_2 \exp(-\alpha d))/(1 - R_1 R_2 \exp(-2\alpha d)) \qquad (4)$$

This allows a calculation of the responsivity, in terms of the electrical current in Amperes per incident light power in Watts, of solar cells of different thickness, d, for different wavelengths, λ, since the absorption coefficient, $\alpha(\lambda)$, is a function of wavelength. If it is assumed that the backside is an ideal reflector, $R_2 = 1.0$, and the amount of diffusive scattering of the back surface varies from that of a planar surface then the fraction of light reflected back from the front surface will vary. If the back surface is planar then there is only specular reflection and, $R_1 = 0.3$, if the back surface is an ideal Lambertian diffusive surface then the fraction of light reflected back from the front surface will be very large, $R_1 = 0.97$. Several values of R_1 are discussed herein for a diffuse reflector, these represent the fraction of light internally reflected back at the front surface. For purposes of the present invention, values of $R_1 \geq 0.9$ are deemed particularly useful. The enhancement in absorption described by Equation 4 then varies with the fraction of light radiation reflected back from the front surface and thickness of the sample.

[0035] FIG. **5** compares the responsivity of a thick (d=200 μm) crystalline solar cell as the reflectivity, R_1, of the back surface is varied. When both the top surface and the back surface are planar (R.sub.1=0.3), the response is indicated by curve **501**, only 30% of the light is reflected back from the front surface and the estimated short circuit current for a solar cell of one square centimeter is 33 mA. The effect of varying R.sub.1 is shown by the other curves, **502**, **503**, and **504**, for

which $R_1 = 0.5$, $R_1 = 0.7$ and $R_1 = 0.9$, respectively. Thus, a Lambertian diffusive reflecting back surface provides the optimum responsivity.

[0036] FIG. **6** is a graph of the calculated responsivity of one square centimeter thin film microcrystalline silicon solar cell with a scattering at the back surface and with a reflector. There can be varying values of the amount of light reflected back from the front surface of 30%, 50% and 90%. If $R_1 = 0.9$, curve **601**, then most of the energy in the red and infrared incident radiation is absorbed and a short circuit solar cell current of 25 mA is calculated. Thus, the conversion efficiency approaches that of thick crystalline solar cells that are one hundred times thicker. The other curves, **602** and **603**, show the effect of varying R_1 to values of 0.7 and 0.5, respectively.

[0037] A thin solar cell/photodetector is shown in FIG. **7**. This solar cell differs from the one described by Aberle in that a thin textured Lambertian scattering back surface **703** is backed by a thin reflecting surface **709** rather than a thick layer of white paint a many times thicker than the solar cell, up to 80 micrometers thick, as in a Pigmented Diffuse Reflector (PDR) with embedded titanium oxide nanoparticles. The solar cell as disclosed herein is either a crystalline p-i-n diode or a microcrystalline p-i-n diode. The semiconductor junction layer **701** at the back and the semiconductor junction layer **702** at the front are any of conventional implanted or diffused junctions or, for heterojunctions, doped amorphous silicon layers. For optimum infrared and long wavelength red response, the backside is textured with a Lambertian scattering layer **703**, the scattering region may be due to a treatment of the silicon material or of the oxide layer, and backed by a reflecting layer **709**, white the front side is a reflective planar surface **704**. As shown before a very large enhancement can be obtained in the infrared response by the total internal reflection of the incident infrared light, represented by arrow **710**, incident on the backside diffuse scattering surface **703** and reflector **709**. Thin layers of microcrystalline are used for solar cells and multiple internal reflections used to increase the absorption of infrared and the longer wavelengths of visible red light. Thus, an embodiment is an amorphous microcrystalline-amorphous silicon thin film n-i-p heterojunction solar cell. The front side **704** has an oxide or transparent conductive oxide layer **705** that is anti-reflecting to visible light, although this anti-reflecting property may be omitted in alternate embodiments, and electrical contacts **706**. The backside has an oxide or transparent conductive oxide layer **707** and electrical contacts **708**.

[0038] An alternative embodiment is to use front side texturing for the semiconducting substrate that provides diffusive scattering to infrared light. This alternative results in increased path lengths and increased absorption for infrared radiation, particularly if the backside of the substrate is reflective or a reflective metal contact. The enhancement of the absorption of infrared light energy wilt not be as great as it can be with backside diffusive scattering since the number of passes is limited; it is easier for the infrared light reflected from the back to escape out of the textured front than it would be to escape from a planar front side. As a result the average number of passes of infrared light that is not strongly absorbed is estimated to be limited to about three; still, some significant increase in energy conversion efficiency of solar radiation can be achieved since the individual path lengths of scattered light are greater than the thickness of the substrate. As before the textured front side that provides diffusive scat-

tering to infrared light can be covered with a layer of conductive or insulating oxide that is anti-reflecting to visible light. This then also ensures optimum absorption of visible light.

[0039] FIG. **8** is a cross section of a stacked pair of solar cells/photodetectors **800**, **700** which receive incident electromagnetic radiation, illustrated by arrow **810**, at a front surface of cell **800**. The band of electromagnetic radiation that encompasses visible light is primarily absorbed, that is, converted to electricity, in cell **800**. The band of electromagnetic radiation that encompasses infrared and long wavelength red light is primarily absorbed in cell **700**. The maximum benefits of texturing can be achieved by using a structure consisting of the two stacked solar cells, as shown. As used herein the term stacked means two separate solar cells, one mounted atop the other with a gap between them. Consider the arrangement in which a semiconductor solar cell **700**, as previously described in relation to FIG. **7**, is oriented such that a second semiconductor solar cell **800** is interposed between the cell **700** and the source of incident radiation. Herein, such an arrangement will deem solar cell **800** to be the top cell and solar cell **700** to be the bottom cell. The bottom cell semiconductor junctions at the back, **701**, and front, **702**, can either be conventional implanted or diffused junctions or doped amorphous silicon layers to form heterojunctions. The top cell semiconductor junctions **802**, **804** are first and second amorphous silicon junction diode materials disposed substantially in planes parallel to a front layer. The top solar cell **800** has a textured front layer **801** that transmits and allows absorption of visible light within top cell **800**, and a textured back layer **803**. Layer **801** is textured to transmit visible and infrared light and the texture of back layer **803** transmits infrared light. The bottom solar cell **700** has a smooth front layer **704** and textured back layer **703** that scatters infrared light energy. Most infrared light, depicted as arrow **810**, just passes through the top solar cell **800** and is not absorbed; the front textured layer **801** and back textured layer **803** in the top solar cell **800** are designed to be an antireflective layers that just transmit infrared light. The bottom solar cell **700** absorbs most of the infrared light energy due to multiple internal reflections and trapping of the infrared light, as described in conjunction with FIG. **7**. The planar front surface **704** is internally reflective to infrared light that is scattered and reflected from the backside. The planar front surface **704** has disposed thereon an oxide or transparent conductive oxide **705** that has electrical contacts **706**, and has, at the option of the designer, anti-reflecting properties to visible light. The backside of cell **700** has an oxide or transparent conductive oxide layer **707** and electrical contacts **708**.

[0040] The front side of cell **800** has an oxide or transparent conductive oxide layer **805**, that may or may not be anti-reflecting to visible light, disposed on the textured front layer **801** and electrical contacts **806**. The backside of cell **800** has an oxide or transparent conductive oxide layer **807** disposed on textured back layer **803** and electrical contacts **808**. Each of the electrical contacts makes a very low resistance connection to the silicon and its associated oxide layer, that is, electrical contacts **706** electrically connect to oxide layer **705**, electrical contacts **708** electrically connect to oxide layer **707**, electrical contacts **806** electrically connect to oxide layer **805**, and electrical contacts **808** electrically connect to oxide layer **807**. Electrical contact between the two cells **800**, **700** is provided by backside contacts **808** and front side contacts **706**, respectively. The efficiency of stacked or tandem cells **800** will be about 25% higher than a single cell.

[0041] A variation to the embodiment of FIG. **8** employs a stacked configuration of textured amorphous silicon, microcrystalline-amorphous silicon thin film n-i-p heterojunction solar cells. It is to be noted that this configuration is different than the tandem configuration described in the aforementioned Choi patent. The present stacked configuration has a large discontinuity in the index of refraction between the two cells **800**, **700** by virtue of having a space between the cells, which is also useful in enabling electrical connections between the cells; the Choi tandem configuration is all one material and does not have this. This discontinuity in the index of refraction due to the space is responsible for multiple internal reflections in the bottom cell **700**.

[0042] An alternative embodiment allows the cells to be one continuous piece of material, as in the Choi tandem cell configuration, without a discontinuity in the index of refraction at the center but with a planar front and textured back with reflector. This arrangement also results in total internal reflections and light trapping and has not been disclosed by Choi.

[0043] Texturing of the backside layer of photodetectors or solar cells can be accomplished by any one of several well known techniques, where these include the removal of silicon material by chemical etchants, plasma etching, porous silicon etchants, lasing to produce black silicon, anisotropic etches like KOH, texturization by sodium carbonate, masking to produce nanostructures by isotropic etch of the silicon, and masking techniques including nanoimprint masks. Diffusive layers are most easily produced by etches, like porous silicon etches, that produce random features. Porous silicon structures have been described in Tsuo for the front side of substrates to reduce reflectance of visible light. However, such structures have not been described for the backside of substrates to produce diffusive reflectance of red and infrared light. As considered herein, diffuse reflective layers that are added to the backside of photodetectors or solar cells are random features that produce diffusive layers at selected wavelengths for incident electromagnetic energy, where these structures include hemispherical grains of polysilicon, titanium oxide nanoparticles embedded in oxide, Atomic Layer Deposition (ALD) of metals, and hexagonal nanocystals produced by diffusion of metals like tungsten or tantalum into amorphous silicon. Grains or nanoparticles are random features that produce diffusive layers for incident light. If necessary to increase reflectivity the structures formed are covered with oxide or transparent conductive oxide and a reflective metal layer.

[0044] The backside texturing described herein preferably produces diffusive scattering of light, either forward diffusive scattering, reflected diffuse scattering or both. This diffuse scattering is to be distinguished from specular reflection and reflections from regular geometric structures and shapes. Regular geometric structures and shapes like trenches, ridges, saw tooth patterns, or pyramids or etch structures produced by KOH alone will only reflect or scatter light at specific angles with respect to the incident light and is not diffusive. Although Mandelkorn describes a ground and silvered bottom glass cover plate separated from the substrate, Mandelkorn does not describe structures etched into or deposited on to the substrate. Ground structures of regular sizes, such as those taught by Mandelkorn, are not diffusive and because of separation from the substrate the light reflected into the substrate will be refracted towards the normal and not diffusive. The Green patent ridges and pyramids etched into the sub-

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strate, but these produce reflections only at specific angles and are not diffusive. The Matsuyama patent discloses solar cells CVD deposited upon opaque substrates with linear recesses, unlike the present solar cells disclosed herein, which have random irregularies of various sizes etched or deposited on planar surfaces. The material at the backside of the cell or deposited on the backside of the solar cell disclosed herein is reflective, not simply opaque. Diffuse scattering produced by random features occurs over a range of angles at the desired band of wavelengths and in the present invention approaches the ideal Lambertian scattering. Ideal reflective Lambertian scattering provides light distributed over the whole half sphere or a solid angle of 2π sterradians. Herein the use backside texturing provides diffusive reflective light scattering at the backside and planar front side surfaces to provide for total internal reflections at the front side and multiple passes of red and infrared light in silicon solar cells. The front surface preferably has an anti-reflecting layer for visible light, but this layer does not significantly effect the reflectivity of the front surface to infrared light.

[0045] Thus, a solar cell/photodetector has been described that provides optimal conversion of visible light and infrared energy to electricity. Backside texturing with diffusive scattering and frontside internal reflection produce a large enhancement of conversion efficiency.

What is claimed is:

1. A semiconductor imager capable of absorbing infrared light, comprising:

a plurality of photodetectors each comprising:

a semiconductor substrate having a substantially planar first surface available to receive incident radiation and a second surface opposite the first surface; and

a light diffusing region optically coupled to the second surface wherein the light diffusing region is configured to scatter light in a substantially Lambertian scattering pattern.

2. The semiconductor imager of claim 1, further comprising a reflecting layer coupled to the light diffusing region.

3. The semiconductor imager of claim 1, wherein the reflecting layer is comprised of a material selected from the group consisting of: oxide, silicon oxide, transparent conductive oxide, metals, and any combinations thereof.

4. The semiconductor imager of claim 1, wherein the semiconductor substrate is comprised of silicon.

5. The semiconductor imager of claim 1, wherein the semiconductor substrate has a thickness in the range of about 1 micrometers to about 10 micrometers.

6. The semiconductor imager of claim 1, wherein the light diffusing region includes features being formed on or within the light diffusing region.

7. The semiconductor imager of claim 6, wherein the features of the light diffusing region are selected from the group consisting of: cones, pyramids, pillars, protrusions, and combinations thereof.

8. The semiconductor imager of claim 1, further comprising an anti-reflective layer disposed at the first surface of the semiconductor substrate and being transparent to infrared electromagnetic radiation.

9. The semiconductor imager of claim 8, wherein the anti-reflective layer include features selected from the group consisting of cones, pyramids, pillars, protrusions, and combinations thereof.

10. The semiconductor imager of claim 9, wherein the features of the anti-reflective layer are randomly distributed on or within the anti-reflective layer.

11. The semiconductor imager of claim 6, wherein the features are formed by a process selected from the group consisting of: chemical etchants, plasma etching, porous silicon etchants, lasing, anisotropic etches, isotropic etches, masking techniques, nanoimprinting and combinations thereof.

12. The semiconductor imager of claim 1, further comprising an oxide material coupled to the second surface of the substrate.

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