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(54) [TITLE OF THE INVENTION] LIGHT-CONFINING STRUCTURE AND PHOTODETECTOR USING THE SAME

(57) [ABSTRACT]
[PURPOSE] To provide a light-confining structure which reduces surface reflection and enables efficient light confinement.
[CONSTITUTION] A transition layer 2 having recesses and protrusions is provided on the front surface of a substrate 3, and the repeating width 7 of the recesses and protrusions is made to be not greater than the wavelength of main light 4 to be confined. Recesses and protrusions 8 and 9 are preferably provided on the rear surface of the substrate 3. The refractive index of the transition layer 2 is varied so as to approach the refractive index of the substrate toward the substrate side from the opposite side as the substrate.

FIG. 7

2...TRANSITION LAYER
4...LIGHT
7...REPEATING WIDTH
8, 9...RECESSES AND PROTRUSIONS

[SCOPE OF THE PATENT CLAIMS]
[CLAIM 1] A light-confining structure comprising a substrate and a transition layer having recesses and protrusions provided on the substrate front surface, wherein a repeating width of the recesses and protrusions is not greater than a wavelength of main light to be confined.
[CLAIM 2] The light-confining structure according to claim 1, wherein a refractive index of the transition layer varies so as to approach a refractive index of the substrate toward the substrate side from the opposite side as the substrate.
[CLAIM 3] The light-confining structure according to claim 1, wherein the transition layer comprises a first material portion having recesses and protrusions disposed on the substrate side and a second material portion having corresponding recesses and protrusions of the opposite orientation disposed on the opposite side as the substrate; and a refractive index of the first material is the same as the refractive index of the substrate or is closer to the refractive index of the substrate than the refractive index of the second material.
[CLAIM 4] The light-confining structure according to claim 3, wherein a shape of the recesses and protrusions is configured so that an area occupying a plane of the second material portion decreases toward the substrate direction from the surface of the transition layer.
[CLAIM 5] The light-confining structure according to claim 4, wherein a shape of the recesses and protrusions is configured so that a ratio at which the area occupying the plane the second material portion decreases toward the substrate direction from the surface of the transition layer is greater near the front surface than near the rear surface of the transition layer.
[CLAIM 6] The light-confining structure according to claim 1, wherein the recesses and protrusions have a substantially triangular cross-sectional shape.
[CLAIM 7] The light-confining structure according to any one of claims 1 to 6, wherein the main light to be confined is visible light, and the repeating width of the recesses and protrusions is not greater than 1 μm.
[CLAIM 8] The light-confining structure according to any one of claims 1 to 7, wherein the substrate has, on the rear surface thereof, second recesses and protrusions having a repeating width greater than the wavelength of the light to be confined.
[CLAIM 9] The light-confining structure according to any one of claims 1 to 8, wherein the substrate has a light-reflecting layer on the rear surface thereof.
[CLAIM 10] A photodetector using the light-confining structure according to any one of claims 1 to 7, wherein the substrate is of a first conductivity type, and the photodetector has an second conductivity type region provided on the substrate and an electrode connected thereto.
[DETAILED DESCRIPTION OF THE INVENTION]
[0001]
[INDUSTRIAL FIELD OF APPLICATION] The present invention relates to a light-confining structure to be used in a light-receiving device such as a light sensor or photovoltaic device or a light-to-light conversion device such as a photoexcitation laser, and a photodetector using the same.
[0002]
[CONVENTIONAL TECHNOLOGY] When irradiating a substrate with light and then using this to perform light-to-light conversion, light-to-electricity conversion, or the like, the efficiency of each type of conversion can be increased by effectively introducing light into the substrate and confining the light inside the substrate without allowing it to escape to the outside of the substrate. To do so, the reduction of the refractive index of light on the substrate surface and the confinement of light incident inside the substrate are crucial.
[0003] Conventionally, the reduction of the refractive index of incident light on the substrate surface has been achieved using an antireflection film or surface recesses and protrusions of a size of around a few tens of μm. In addition, as described in SID 89 DIGEST p270 (1989) or Japanese Patent Application No. H03-54371, an antireflection film having minute surface recesses and protrusions formed using fine SiO_2 and MgF_2 powders has been used.
[0004]
[PROBLEM TO BE SOLVED BY THE INVENTION] The conventional method using an antireflection film described above was problematic in that it was not possible to sufficiently reduce the refractive index when the wavelength of incident light varied over a wide range or the angle of incidence of light varied substantially. Moreover, the method using surface recesses and protrusions of a size of around a few tens of μm was problematic in that, since the optical path is bent substantially by refraction when light is incident on the substrate, it is difficult to perform light confinement using recesses and protrusions formed on the rear surface. Further, when an antireflection film having minute surface recesses and protrusions formed using a fine SiO_2 powder or the like was used, there was a problem in that it was difficult to make the refractive reflex very low because the refractive index of the substrate or the shape of the minute surface recesses and protrusions was not taken into consideration.
[0005] An object of the present invention is to provide a light-confining structure which reduces surface reflection and enables efficient light confinement, and a photodetector using the same.
[0006]
[MEANS FOR SOLVING THE PROBLEM] To achieve the object described above, the light-confining structure of the present invention comprises a substrate and a transition layer having recesses and protrusions provided on the substrate front surface, wherein the repeating width of the recesses and protrusions is not greater than the wavelength of main light to be confined.
[0007] The refractive index of the transition layer preferably varies so as to approach the refractive index of the substrate toward the substrate side from the opposite side as the substrate. When the refractive index varies continuously in the substrate direction from the exterior of the substrate, a refractive index that is much lower than that of an antireflection film consisting of a thin interference film formed from several layers can be achieved over a wide range of wavelengths.
[0008] In addition, it is preferable for the transition layer to comprise a first material portion having recesses and protrusions disposed on the substrate side and a second material portion having corresponding recesses and protrusions of the opposite orientation disposed on the opposite side as the substrate; and for the refractive index of the first material to be the same as the refractive index of the substrate or to be closer to the refractive index of the substrate than the refractive index of the second material. The first material portion may be formed using the substrate itself – for example, it may be a portion in which recesses and protrusions are formed on the surface of the substrate, or it may be a portion in which another material is affixed to the surface of the substrate. The second material portion may be air or may have a structure in which the spaces between the recesses and protrusions of the surface of the substrate are filled with another material.
[0009] The shape of the recesses and protrusions is preferably configured so that the area occupying the plane of the second material portion decreases toward the substrate direction from

the surface of the transition layer. The repeating width of the recesses and protrusions is preferably not greater than 1 μm when the main light to be confined is visible light.

[0010] In addition, the light-confining structure of the present invention may be provided with, on the rear surface thereof, second recesses and protrusions having a repeating width greater than the wavelength of the light to be confined. Further, a light-reflecting layer may be provided on the rear surface of the substrate.

[0011] Further, the photodetector of the present invention uses the light-confining structure described above, wherein when the substrate is given a first conductivity type, a second conductivity type region of the opposite conductivity type as the first conductivity type is provided on the substrate, a first conductivity type region of an even higher concentration is preferable provided on the substrate, and an electrode for connecting the regions is provided.

[0012]

[EFFECT] The effect of the present invention will be described using FIGS. 1 to 6. FIGS. 1(a) and (b) are a partial perspective view of the vicinity of the front surface of a substrate and a cross-sectional view thereof. When light 4 is incident on a substrate 3 from an external medium 1 and a repeating width 7 of recesses and protrusions of the surface of the substrate is smaller than the wavelength of the light, there is an optical effect that is the same as the case in which the refractive index of a transition layer 2 varies continuously toward the substrate from the front surface. That is, as illustrated in the drawings, when the ratio of a second medium 5 to a first medium 6 varies gradually toward the substrate, a transition layer 2 is formed which is equivalent to a film in which the refractive index varies linearly from the refractive index of the second medium 5 to the refractive index of the first medium 6.

[0013] The state of change in the refractive index within the transition layer is determined by the manner in which first medium and the second medium are mixed. In a film consisting of two types of mediums, the effective refractive index thereof is expressed by the average value of the respective mediums. As illustrated in FIGS. 2(a), (b), (c), (d), (e), and (f), when the respective first medium 6 has a shape such as a rectangle, triangular groove, pyramid, semispherical shape, spherical shape, or inverted pyramid shape and the refractive index of the second medium 5 is set to 1.0 while the refractive index of the first medium 6 is set to 3.5, the effective refractive index is as illustrated in FIG. 3.

[0014] The calculated refractive index for a pyramid and spherical shape when the refractive index of the external medium 1 is set to 1.0, the refractive index of the second medium 5 is set to 1.0, the refractive index of the first medium 6 is set to 3.5, and the refractive index of the substrate 3 is set to 3.5 is illustrated in FIG. 4. FIGS. 4(a) and (b) illustrate the refractive index in the case of a pyramid shape, and FIGS. 4(c) and (d) illustrate the refractive index of a spherical shape in a linear scale and a logarithmic scale, respectively. In the case of a pyramid shape, a somewhat high refractive index is observed when the film thickness of the transition layer is 40 nm, but a very low refractive index is observed when the film thickness is greater than this. In the case of a spherical shape, the refractive index exceeds 10% on average at any film thickness, and a slightly higher refractive index is observed in comparison to a pyramid shape.

[0015] FIG. 5 illustrates the relationship between the amount of light absorption and the film thickness of the transition layer in the case of a pyramid shape. The illustrated results are calculated for a case in which the refractive index of the external medium 1 is set to 1.0, the refractive index of the first medium 6 is set to 3.5, the refractive index of the substrate 3 is set to 3.5, and the refractive index of the of the second medium 5 is set to 1.0 and 1.5. In each case, the amount of light absorption becomes large when the film thickness of the transition layer is around a few hundred nm, and there is approximately 100% absorption at film thicknesses greater than this.

[0016] FIG. 6 illustrates the relationship between the amount of light absorption and the film thickness of the transition layer in the case of each shape. The illustrated results are calculated for a case in which the refractive index of the external medium 1 is set to 1.0, the refractive index of the of the second medium 5 is set to 1.0, the refractive index of the first medium 6 is set to 3.5, and the refractive index of the of the substrate 3 is set to 3.5. The amount of light absorption at each film thickness is greatest with a pyramid shape, and a high amount of absorption is observed up to an inverted pyramid shape. However, with a rectangular and spherical shape, the amount of light absorption is not large, even when the film thickness of the transition layer is increased. This result demonstrates that the amount of light absorption is large when the shape of the first medium is such that it rises upward to the right in FIG. 3. In addition, the fact that a pyramid shape which rises upward to the right and has a falling convex curve in FIG. 3, in particular, demonstrates that a shape in which the ratio of decrease in area in the substrate direction of the second medium 5 near the front surface of the transition layer 2 is greater than the ratio of decrease near the rear surface of the transition layer 2 is preferable, as in the case of a pyramid shape, a polygonal pyramid shape, a cone, or a shape obtained by rotating a line segment downward.

[0017] The specific substrate shape will be described using FIG. 7. As illustrated in FIG. 7(a), a transition layer 2 consisting of recesses and protrusions with a small repeating width 7 is provided on a substrate. As a result, the refractive index of the transition layer 2 varies continuously from the refractive index of the outside air to the refractive index of the substrate 3 from top to bottom. This transition layer allows light 4 that is incident on the substrate 3 to reach the inside of the substrate without being substantially reflected by the substrate surface. In addition, since the repeating width 7 is smaller than the wavelength of the incident light, the incident light proceeds directly to the rear surface of the substrate at the angle of incidence without being reflected diagonally by the inclined surfaces formed by the recesses and protrusions of the front surface of the substrate.

[0018] By forming recesses and protrusions 8 having a repeating width that is larger than the wavelength of the incident light with a period such as that illustrated in FIG. 7(b) on the substrate, light that is reflected by the rear surface advances diagonally through the inside of the substrate and reaches the front surface of the substrate. When the angle of incidence at this time is greater than a critical angle, the light is completely reflected and proceeds back through the inside of the substrate. In this way, incident light is efficiently confined in the substrate 3. In addition, by forming irregular recesses and protrusions 9 having a repeating width that is larger than the wavelength of the incident light on the rear surface, as illustrated in FIG. 7(c), light is scattered and reflected by the rear surface, and most of the light has an angle of incidence that is greater than the critical angle when it reaches the front surface of the substrate, allowing the incident light to be efficiently confined in the substrate 3. In these configurations, forming a reflective mirror on the rear surface makes it possible to more reliably reflect light with the rear surface.

[0019]

[EXAMPLES] <Example 1> An example of the present invention will be described using FIG. 8. In this example, pyramids 11 which constitute a transition layer and have a regular width and size are formed on a silicon substrate 3 in which the surface is a (100) plane. The pyramids can be easily formed by masking the rear surface and processing only the front surface with an alkaline etching solution. In addition, minute pyramids 11 not larger than 1 μm can be easily formed by processing using as an etching solution a heated aqueous solution containing ammonia or hydrazine as a main component.

[0020] The average size of the pyramids 11 on the front surface of the silicon substrate 3 obtained in this way was around 0.3 μm according to measurements with an SEM (scanning electron microscope). When the surface reflectance of the silicon substrate was measured, the surface reflectance decreased dramatically in the wavelength range of 0.4 to 1.1 μm. When a film formed from a thin oxide film was provided on the front surface of the silicon substrate 3, the change in the refractive index inside the transition layer 2 became rapid, and the reflectance of the front surface dropped further.

[0021] <Example 2> Another example of the present invention will be described using FIG. 9. In this example, minute recesses and protrusions 11' of irregular size having cross sections that were primarily triangular were formed on a silicon substrate 3. The minute recesses and protrusions 11' were formed by a deposited film using CVD (chemical vapor deposition). The material of the film that was used was a material that is transparent and has a relatively high refractive index such as ITO or ZnO_2. The size of the minute recesses and protrusions 11' was set on average to around 0.5 μm by controlling the deposition speed, temperature, gas pressure, and the like. In addition, the spaces between the minute recesses and protrusions 11' were filled with a filling material (not illustrated) to protect the front surface. A material with a relatively small refractive index such as SiO_2 was formed on the filling material by means of spin coating, CVD, or the like. The reflectance of the front surface of this silicon substrate also decreased dramatically in the wavelength range of 0.4 to 1.1 μm.

[0022] <Example 3> Yet another example of the present invention will be described using FIG. 10. In this example, V-grooves 13 with a repeating width of 2 μm were formed on the rear surface of the silicon substrate 3 described in Example 2. As a result, light incident from the front surface is reflected by the rear surface and is completely reflected when it reaches the front surface again, allowing the light to be confined inside the silicon substrate. The V-grooves 13 were easily formed using an etching mask using an ordinary photoresist. In this case, a printing resist may also be used instead of a photoresist. In addition, the shape of the rear surface is not limited to V-grooves and may be a shape such as inverted pyramids or semispherical shapes as long as the size is such that the repeating width is greater than the wavelength of the incident light. A rear surface reflecting mirror 14 was also formed to increase the rear surface reflectance.

[0023] <Example 4> Yet another example will be described using FIG. 11. In this example, pyramidal recesses and protrusions 15 were formed on the rear surface of a silicon substrate 3. Transparent glass was used for the material of the recesses and protrusions 15, and the glass was adhered to the silicon substrate 3. As a result, a light-trapping structure was easily formed by processing the silicon substrate 3. In addition, as in Example 3, a rear surface reflecting mirror (not illustrated) was formed.

[0024] <Example 5> An example of a photodetector will be described using FIG. 12. As in Example 3, minute recesses and protrusions 11' of irregular size having cross sections that were primarily triangular were formed on a p-type silicon substrate 21, and V-grooves having a repeating width of 2 μm were formed on the rear surface (the rear surface reflecting mirror illustrated in Example 3 was not formed). Next, a high-concentration p-type layer 19 and a high-concentration n-type layer 20 were formed by thermal diffusion, and a passivation oxide film 18 was formed on the front and rear surfaces of the p-type silicon substrate 21 (the oxide film of the front surface is not illustrated). Holes were formed in the oxide film 18 at prescribed positions, and electrodes 16 and 17 were formed by vacuum deposition, resulting in the formation of a photodetector. This photodetector exhibited a photoelectric conversion efficiency that was improved over a conventional photodetector not provided with a transition layer consisting of minute recesses and protrusions 11'.

[0025] Note that photodetectors were similarly formed using p-type silicon substrates having transition layers with minute recesses and protrusions of shapes other than those described above – that is, a triangular groove shape, a spherical shape, a semispherical shape, an inverted pyramid shape, and a rectangular shape – and all of the photodetectors exhibited photoelectric conversion efficiency that was improved over a conventional photodetector.

[0026] Silicon was used as a substrate in the above examples, but it goes without saying that any material other than silicon may also be used, including single crystals such as gallium arsenide, indium phosphorus, CuInS, and CdS, polycrystals, amorphous monoatoms, semiconductors such as multicomponent systems, and insulating materials such as glass and plastic. In addition, the structures of the front surface recesses and protrusions and the rear surface recesses and protrusions may be combinations of any of the structures described above, and it goes without saying that the cross-sectional shapes of the recesses and protrusions may be the shapes described in FIG. 2 or any similar regular or irregular shapes.

[0027]

[EFFECT OF THE INVENTION] By using the structure of the present invention, it is possible to effectively confine light when it is necessary to effectively confine light in a light-receiving device such as a light sensor or photovoltaic device or a light-to-light conversion device such as a photoexcitation laser. In addition, the photodetector of the present invention, which uses such a light-confining structure, exhibited improved photoelectric conversion efficiency.

[BRIEF DESCRIPTION OF THE DRAWINGS]

FIG. 1 is a conceptual diagram for explaining the principle of the present invention.

FIG. 2 is a conceptual diagram for explaining the principle of the present invention.

FIG. 3 illustrates an example of calculation results for explaining the effect of the present invention.

FIG. 4 illustrates an example of calculation results for explaining the effect of the present invention.

FIG. 5 illustrates an example of calculation results for explaining the effect of the present invention.

FIG. 6 illustrates an example of calculation results for explaining the effect of the present invention.

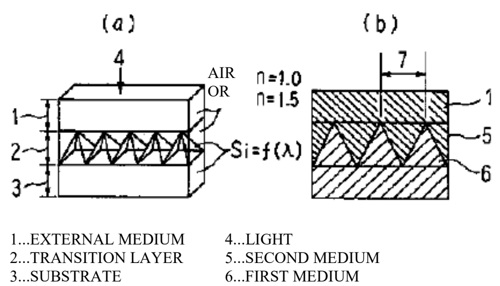
FIG. 7 is a conceptual diagram for explaining the principle of the present invention.

FIG. 8 is a cross-sectional schematic view of an example of the light-confining structure of the present invention.

FIG. 9 is a cross-sectional schematic view and a perspective view of another example of the light-confining structure of the present invention.
FIG. 10 is a perspective view of an example of the light-confining structure of the present invention.
FIG. 11 is a perspective view of an example of the light-confining structure of the present invention.
FIG. 12 is a perspective view of an example of the photodetector of the present invention.
[EXPLANATION OF SYMBOLS]
1...External medium
2...Transition layer
3...Substrate
4...Light
5...Second medium
6...First medium
7...Repeating width
8, 9, 15...Recessions and protrusions
11...Pyramid
11'...Minute recessions and protrusions
13...V-groove
14...Rear surface reflecting mirror
16, 17...Electrodes
18...Oxide film
19...High-concentration p-type layer
20...High-concentration n-type layer
21...p-type silicon substrate

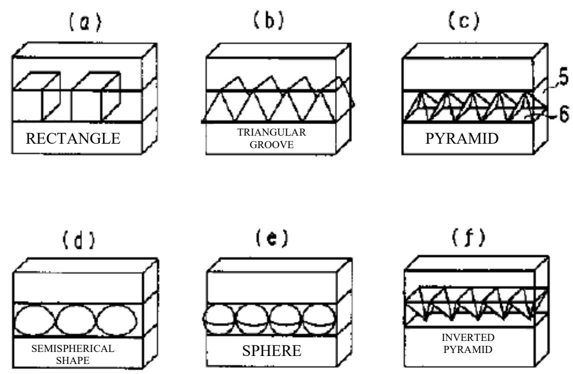
[FIG. 1]

FIG. 1



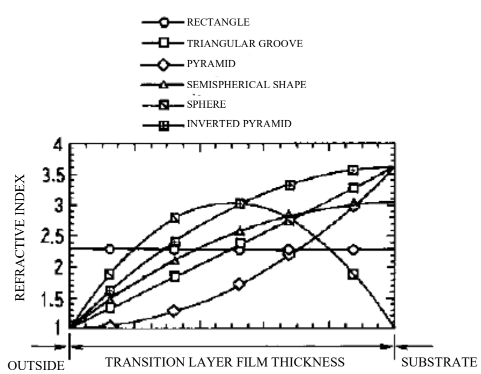
[FIG. 2]

FIG. 2



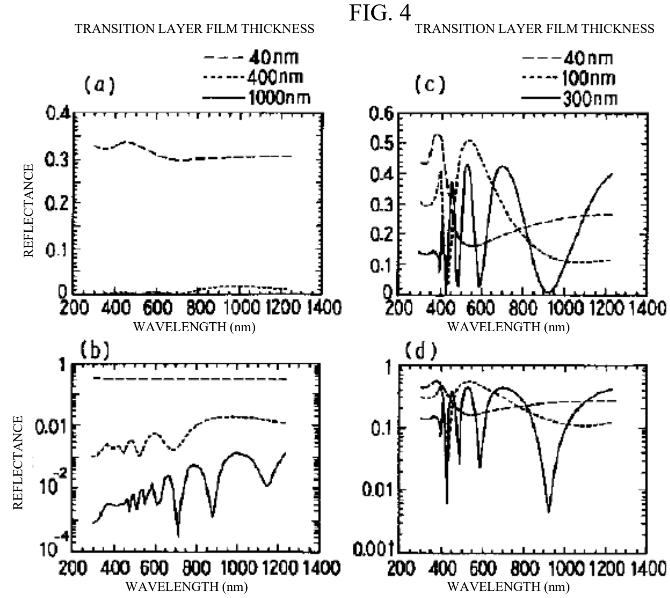
[FIG. 3]

FIG. 3



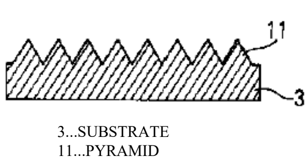
[FIG. 4]

FIG. 4



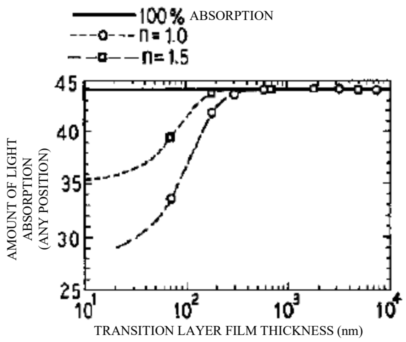
[FIG. 8]

FIG. 8



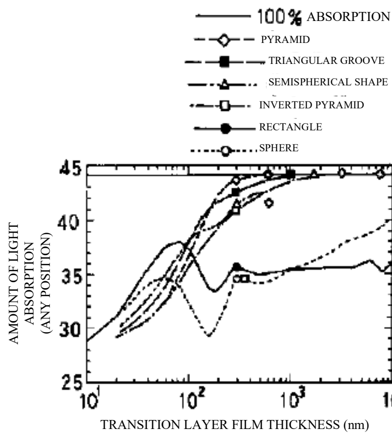
[FIG. 5]

FIG. 5



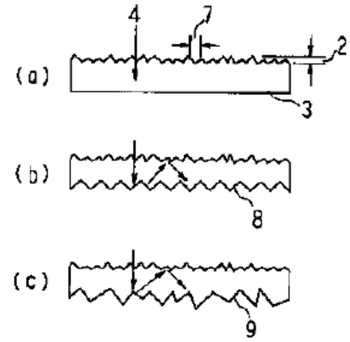
[FIG. 6]

FIG. 6



[FIG. 7]

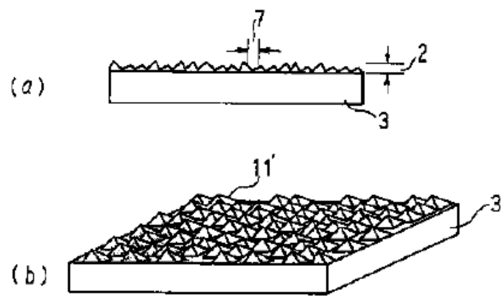
FIG. 7



2...TRANSITION LAYER
4...LIGHT
7...REPEATING WIDTH
8, 9...RECESSIONS AND PROTRUSIONS

[FIG. 9]

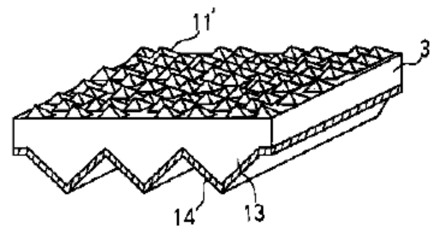
FIG. 9



11'...MINUTE RECESSIONS AND PROTRUSIONS

[FIG. 10]

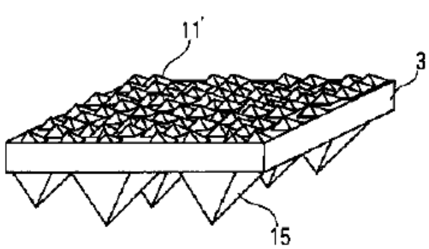
FIG. 10



11'...MINUTE RECESSIONS AND PROTRUSIONS
13...V-GROOVE
14...REAR SURFACE REFLECTING MIRROR

[FIG. 11]

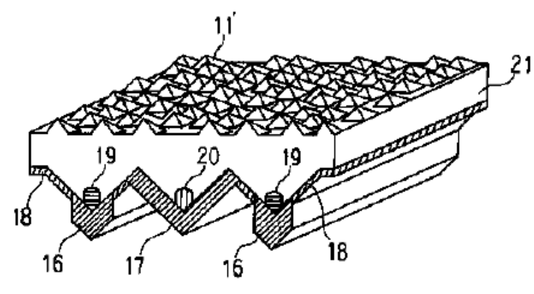
FIG. 11



11'...MINUTE RECESSIONS AND PROTRUSIONS
15...RECESSIONS AND PROTRUSIONS

[FIG. 12]

FIG. 12



11'...MINUTE RECESSIONS AND PROTRUSIONS
16, 17...ELECTRODES
18...OXIDE LAYER
19...HIGH-CONCENTRATION p-TYPE LAYER
20...HIGH-CONCENTRATION n-TYPE LAYER
21...p-TYPE SILICON SUBSTRATE

Continued from the front page

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