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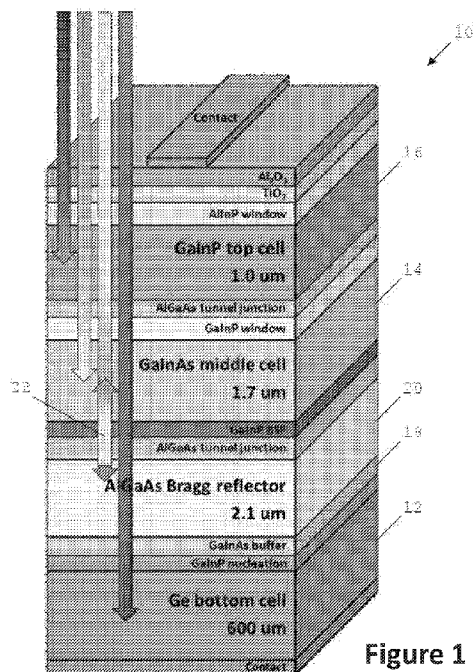


Figure 1

(57) Abstract: Disclosed is a solar cell structure comprising a first material component, a layered structure and a second material component. The first material component comprises a substrate and has a surface. The layered structure forms an interface with the surface of the first material component. The second material component comprises at least one solar cell component arranged to absorb a portion of light within a first wavelength range. The second material component also has a surface at an interface with the layered structure. The layered structure comprises a distributed Bragg reflector (DBR) that is formed from a stack of single layers having selected thicknesses and refractive indices, the DBR being configured to reflect light within a second wavelength range.

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A PHOTOVOLTAIC CELL STRUCTURE

Technical Field of the Invention

5 The present invention relates to a photovoltaic cell structure.

Background of the Invention

10 Improvements in photovoltaic conversion efficiencies have been the subject of extensive research in recent years. A technique that is recognised as an effective approach is spectrum splitting, which involves dividing a solar spectrum received by a solar cell into several spectral
15 bands and directing each band to a semiconductor with a suitably matched band gap. This may be achieved by using dedicated optics such as dichroic filters or mirrors, or employing tandem solar cells including (monolithic or mechanical) a stack of sub-solar cell layers with
20 decreasing band gaps (top to bottom), otherwise known as "multi-junction solar cells", or a combination of both approaches. The abovementioned discrete optical elements usually require complex high-pass, low-pass or bandpass designs consisting of many dielectric layers. In the
25 multi-junction solar cell, each layer is configured to absorb a portion of the solar spectrum in a particular wavelengths range and produce a corresponding electric current.

30 There are various types of multi-junction solar cells. In recent years, metamorphic solar cells, which have a higher degree of lattice mismatch between sub-cells compared to lattice-matched solar cells, have proven to be highly

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efficient. However, due to the lattice mismatch, a buffer layer is implemented between two mismatched sub-solar cells to provide a transition region from the lattice constant of one sub-solar cell to the other.

5

A further improvement in photovoltaic conversion efficiencies may be provided by implementing distributed Bragg reflectors (DBR) into the solar cell. A DBR comprises a periodic structure formed from multiple
10 alternating layers of materials with different refractive index. A DBR can achieve nearly 100% reflectance over a specific wavelength range. Implemented in a solar cell, a DBR can reflect non-absorbed photons back towards a sub-cell for an additional attempt at absorption by the cell,
15 or towards a separate solar cell, allowing an increase in photocurrent and efficiency.

It may be desirable to provide further improvements or alternatives to photovoltaic conversion efficiencies.

20

Summary of the Invention

In broad terms, embodiments of the present invention relate to the incorporation of a DBR within a buffer layer
25 of a solar cell structure, such as a metamorphic solar cell structure.

According to a first aspect, there is provided a solar cell structure comprising:

30 a first material component comprising a substrate and having a surface;

a layered structure forming an interface with the surface of the first material component; and

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a second material component comprising at least one solar cell component arranged to absorb a portion of light within a first wavelength range, the second material component having a surface at an interface with the
5 layered structure;

wherein the buffer layer structure comprises a distributed Bragg reflector (DBR) that is formed from a stack of single layers having selected thicknesses and refractive indices, the DBR being configured to reflect
10 light within a second wavelength range.

The second material component can have, at the surface at the interface to the layered structure, a lattice constant that differs from a lattice constant of the first material
15 at the interface to the layered structure. The DBR is part of or comprises a buffer for the solar cell structure

By integrating a buffer layer structure with a DBR, manufacturing costs may be reduced.

20

The buffer layer structure in some embodiments of the present invention has at least the following functions. The buffer layer structure provides transition for lattice mis-match between the surface of first material component
25 and the surface of second material component. Further, the buffer layer structure incorporates, and functions, as a DBR.

The second wavelengths range can be 850nm to 950nm, 950
30 to 1050 nm, 900 to 1000nm or 900 to 1050nm.

The second wavelength range may at least partially overlaps with the first wavelength range in which in use

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the at least one solar cell component absorbs light. Alternatively, the second wavelength range does not overlap with the first wavelength range.

5 The DBR may be configured to reflect, dependent on an angle of incidence of incoming light, light back towards the at least one solar cell component of the second material component and/or out of the solar cell structure for absorption by another solar structure. The other solar
10 structure can be silicon based, such as one comprising a silicon solar cell, or a stack of two or more solar cells including a silicon solar cell.

The layered structure may comprise a periodic structure.
15 The periodic structure may comprise multiple alternating single layers, arranged so that single layers of two or more types of different materials alternate in the periodic structure. The single layers may be step-graded layers each having a lattice constant, wherein the lattice
20 constants of the step-graded layers overall or in general increases in one direction along the periodic structure.

There may be a decrease in the lattice constants from at least one of the step-graded layer to next adjacent step-
25 graded layer in the one direction along the periodic structure, but the lattice constants overall increase in the direction along the periodic structure.

A composition of each type of material of the layered
30 structure may gradually change in one direction along the stack of layers. For example, a first type of material of the layered structure may be GaInAs, a second type of material of the layered structure may be GaInP. In

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particular, the first type of material of the layered structure comprises $Ga_xIn_{1-x}As$ and the second type of material of the layered structure comprises $Ga_yIn_{1-y}P$ with x and y gradually decreasing in one direction along the stack of layers

In one specific example the buffer layer structure comprises alternating single layers of two material types.

Alternatively, the buffer layer structure may comprise three or more types of material, which may be ordered in periods comprising three or more single respective layers with the periods repeating a plurality of times.

The single layers of the buffer layer structure may have a thickness ranging from 50nm to 100nm. The number of single layers in the layered structure can vary, from 5 - 10, 10 - 15, to 15 - 20 or more single layers.

The first material component may also comprise at least one further solar cell component, which may for example comprise germanium, and which is in use positioned below the buffer layer structure and above the substrate.

The at least one further solar cell component can comprise germanium, GaAs, or InP.

The solar cell structure may comprise at least two solar cell components that are located within the second material component and in use located above the layered structure, such that in use the DBR reflects a portion of light that travelled through the at least two solar cell components back towards the at least two solar cell components for absorption by at least one of the at least

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two solar cell components.

The solar cell structure may comprise a series of solar cell components, which may be ordered such that incoming
5 light travels through a succession of the solar cell components having decreasing band gap energies. The layered structure in this example may be located between two of the series of the solar cell components, and the second wavelengths range that at least partially overlaps
10 with a wavelengths range within which at least one of the solar cell components, which is in use positioned above the layered structure, absorbs light. Alternatively, the second wavelength range does not overlap with another wavelength range within which at least one of the solar
15 cell components, which is in use positioned above the buffer layer structure, absorbs light.

The first material component may comprise more than one
20 solar cells which may comprise GaAs, GaInAs, GaInP or another suitable material, and which are ordered such that incoming light travels through a succession of the solar cells components within the first material component with decreasing bandgap energies.

25

In one specific example solar cell structure may comprise a GaInP-based solar cell component, a GaInAs-based solar cell component and a Ge-based solar cell component. The layered structure in this example may be positioned
30 between the GaInAs-based solar cell component and the Ge-based solar cell component.

The solar cell structure may also comprise at least one

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further DBR, configured to reflect light within at least a third wavelength range. The third wavelength range may be different from the second wavelength range. The at least one further DBR may be positioned in the proximity of the layered structure.

The at least one further DBR may in use be positioned above or below the layered structure.

10 A surface of the at least one further DBR may form the interface between the layered structure with the first or second material components.

The second material component may comprise the at least one further DBR, which may form the interface with the layered structure. Alternatively, the first material component may comprise the at least one further DBR, which may form the interface with the layered structure.

20 The at least one further DBR may comprise a plurality of stacked bilayers or trilayers.

Each bilayer may comprise two or three different materials having different reflective indices, such that a periodic structure is formed.

The different materials in each bilayer or trilayer may have the same or similar lattice constants.

30 In one specific example the materials of the bilayers or the trilayers comprise GaInP and GaInAs.

The DBR and at least one further DBR can be each adapted

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to provide peak reflectance at different wavelengths.
In another aspect, the present invention provides a solar
arrangement, including a first solar cell structure as
mentioned above in respect of the first aspect, and a
5 second solar structure which is adapted to receive a light
reflected by the first solar cell structure.

The second solar structure can include at least one
silicon solar cell.

10

Brief Description of the Drawings

Figure 1 is a schematic diagram of a triple-junction solar
cell (TJSC) structure.

15

Figure 2 is a schematic diagram of a TJSC structure with a
multi-layer buffer structure.

Figure 3 is a schematic diagram of a buffer structure
20 comprising a DBR in accordance with an embodiment of the
present invention.

Figure 4 is a schematic diagram of a buffer structure
comprising a DBR in accordance with another embodiment of
25 the present invention.

Figure 5 is a schematic diagram of a buffer structure
comprising a DBR together with an additional DBR in
accordance with another embodiment of the present
30 invention.

Figure 6 is a schematic diagram of a buffer structure
comprising a DBR together with an additional DBR in

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accordance with another embodiment of the present invention.

Figure 7 shows a plot of spectral reflectance as a
5 function of wavelength.

Figure 8 shows another plot of spectral reflectance and wavelength.

10 Figure 9(a) is a plot of the real components of the complex refractive indices of the top, middle, bottom sub-cells and DBR layers in a latticed matched triple junction solar cell, where the DBR layers comprise periodic layers of $\text{Ga}_{0.2}\text{Al}_{0.8}\text{As}$ and $\text{Ga}_{0.8}\text{Al}_{0.2}\text{As}$.

15

Figure 9(b) is a plot of the imaginary components of the complex refractive indices shown in Figure 9a.

Figure 9(c) is a plot of the real components of the
20 complex refractive indices of the anti-reflection coating (ARC) layers and the rear aluminium contact layer in a lattice matched triple junction solar cell.

Figure 9(d) is a plot of the imaginary components of the
25 complex refractive indices shown in Figure 9c.

Figure 10 is a schematic diagram of a TJSC structure with a multi-layer buffer structure.

30 Figure 11 is a plot showing modelled and measured specular reflectance at 8° angle of incidence, in a commercial lattice matched triple junction solar cell (insert shows close-up at wavelengths of interest to spectrum

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splitting).

Figure 12 is a plot of specular reflectance, as a function of wavelength, of a LM TJSC with a spectrum-splitting DBR, in accordance with an embodiment of the invention, optimized to reflect wavelengths in the range of 900-1050 nm at 45° AOI.

Figure 13 is a plot of specular reflectance, as a function of wavelength, of a LM TJSC with a spectrum-splitting DBR, in accordance with another embodiment of the invention, optimized to reflect wavelengths in the range of 900-1050 nm at 45° AOI.

Figure 14 is a plot of specular reflectance, as a function of wavelength, of a LM TJSC with a spectrum-splitting DBR, in accordance with another embodiment of the invention, optimized to reflect wavelengths in the range of 900-1050 nm at 45° AOI.

Figure 15 is a plot of specular reflectance, as a function of wavelength, of a LM TJSC with a spectrum-splitting DBR, in accordance with a further embodiment of the invention, optimized to reflect wavelengths in the range of 900-1050 nm at 45° AOI.

Figure 16(a) is a plot of external quantum efficiencies (EQE) of the top, middle, and bottom sub-cells in a LM TJSC without a DBR buffer, as a function of wavelength.

Figure 16(b) is a plot of external quantum efficiencies (EQE) of the top, middle, and bottom sub-cells in a LM TJSC with a DBR buffer, and the EQE of a silicon solar

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cell receiving the reflected light from the DBR buffer, as a function of wavelength.

Figure 17 is a schematic diagram of the buffer structure shown in Figure 3, with more different thickness information.

Figure 18 is a schematic diagram of the buffer structure shown in Figure 4, with more different thickness information.

Figure 19 is a schematic diagram of the buffer structure shown in Figure 5, with more different thickness information.

Figure 20 is a schematic diagram of the buffer structure shown in Figure 6, with more different thickness information.

Figure 21 depicts a central receiver concentrated photovoltaic (CPV) power tower system, and a ray-trace diagram of one possible (band-reflect) spectrum-splitting receiver.

Figure 22 is a plot depicting angle of incidence versus wavelength, for multi-junction solar cells in accordance with different embodiments of the invention, and for a prior art multi-junction solar cell with a dielectric filter.

30

Detailed Description of Embodiments

As will be explained below, the inventors have recognised

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that the buffer layers provided in TJSC can be modified, so that they provide optical functions, in addition to the structural matching function they traditionally provide. As will be explained below, the inventors have recognised
5 that it is possible to use the DBR layers to boost photo-currents to the sub-cells in the TJSC. Instead, or in addition, by optimising the DBR to function as a suitable band-reflect filter, the DBR can enable photons in a spectral range which is not absorbed by the sub-cells, to
10 be reflected out of the TJSC stack, so that these photons can be captured by a different cell (e.g. a silicon solar cell located to receive the reflected photons).

The present invention provides an alternative approach to
15 spectrum splitting, involving the integration of an intermediate distributed Bragg reflector (DBR), optimized to function as a suitable band-reflect filter. This can be included, for example, in a commercial triple-junction solar cell (TJSC).

20

A DBR is a periodic structure formed from multiple alternating layers of materials with different refractive index. A DBR can achieve nearly 100% reflectance over a specific wavelength range. Implemented in a solar cell, a
25 DBR can reflect non-absorbed photons for an additional pass through the cell, allowing an increase in photocurrent and efficiency.

Figure 1 illustrates an example of a triple-junction solar
30 cell (TJSC) structure 10. In this example, the TJSC structure 10 includes a bottom solar cell component or "sub-cell" 12 based on germanium. The TJSC structure 10 also includes two further sub-cells: a middle sub-cell 14

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comprising GaInAs; and a top sub-cell 16 comprising GaInP.

The solar sub-cells 12, 14, 16 are configured to absorb a portion of the solar spectrum within particular wavelength
5 ranges. As will be appreciated by those skilled in the art, the solar sub-cells 12, 14, 16 have different band gaps that determine which portions of the solar spectrum each sub-cell 12, 14, 16 is capable of absorbing. The sub-cells 12, 14, 16 will only absorb photons having energy
10 levels above their respective band gaps. The TJSC structure 10 is configured such that the sub-cells 12, 14, 16 have progressively decreasing band gaps, with the top sub-cell 16 having the highest band gap and the bottom sub-cell 12 having the lowest band gap.

15

The TJSC structure 10 is considered to be a lattice-matched (LM) TJSC since there is only a slight mismatch between the lattice constants of the bottom sub-cell 12 and the middle sub-cell 14. Nevertheless, the TJSC
20 structure 10 further comprises a relatively thin buffer layer 18 to accommodate for the slight difference in lattice constants.

The TJSC structure 10 further comprises a distributed
25 Bragg reflector (DBR) 20 situated between the middle sub-cell 14 and the bottom sub-cell 12. The DBR 20 has a "spectrum-splitting" effect by directing specific portions of the solar spectrum to specific locations (e.g. solar cells), which will be described in more detail below.

30

The DBR 20 in this example comprises AlGaAs. As will be understood by those skilled in the art, a DBR is a periodic structure formed from multiple layers of

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materials with alternating refractive indices. Although not specifically illustrated, the DBR 20 in this example comprises a stack of 16 bilayers, each bilayer comprising a first layer of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ and a second layer of

5 $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$. Each first layer has a different refractive index to each second layer, and thus when stacked the bilayers provide the periodic structure for the DBR. However, the number of bilayers included in the DBR 20 is not restricted to being 16. Different numbers of bilayers

10 can be used, depending on, e.g., the desired peak reflectance, and the desired spectral range to be reflected.

The DBR 20 reflects photons in a particular wavelength

15 (i.e. spectral) range, which have not been absorbed by the top sub-cell 16 and middle sub-cell 14, back towards those sub-cells 14, 16 for a second attempt at absorption by one or both of the sub-cells 14, 16. The particular wavelength range in which photons are reflected by the DBR 20

20 therefore overlaps with the particular wavelength range(s) at which photons are absorbed by the top and/or middle sub-cells 14, 16. This is illustrated by the arrow 22 in Figure 1. In some examples, the particular wavelengths range in which photons are reflected by the DBR 20 and/or

25 absorbed by one or more sub-cells 14, 16 may be 850nm to 950nm, 950 to 1050 nm, 900 to 1000nm or 900 to 1050nm. In this manner, the conversion efficiency of the TJSC structure 10 is increased since the DBR 20 assists in maximising absorption of solar energy.

30

Alternatively or additionally, the DBR 20 may be designed such that non-absorbed photons are reflected away from the TJSC 10 towards another solar cell (e.g. a Silicon-based

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solar cell, not shown) for collection. For instance, the photons in the near infrared range (e.g. 900nm to 1050nm) will accordingly be reflected out of the solar cell 10 by the DBR 20.

5

Figures 2 illustrates a metamorphic TJSC structure 30. Components that are the same or similar to components of the LM TJSC structure 10 shown in Figure 1 will be given a corresponding reference numeral.

10

Like the LM TJSC structure 10, the TJSC structure 10s comprises a bottom sub-cell 12s comprising germanium, a middle sub-cell 14s comprising GaInAs, and a top sub-cell 16s comprising GaInP. In this specific example, the composition of the top sub-cell 16s is $\text{Ga}_{0.44}\text{In}_{0.56}\text{P}$ and the composition of the middle sub-cell 14s is $\text{Ga}_{0.92}\text{In}_{0.08}\text{As}$.

Unlike the LM TJSC structure 10, the TJSC structure 10s is considered to be a metamorphic TJSC 10s with a higher mismatch between the lattice constants of the bottom sub-cell 12s and middle sub-cell 14s. Accordingly, the TJSC structure 10s also includes a buffer structure 18s that is thicker than the buffer layer 18 of the LM TJSC structure 10s. The buffer structure 18s comprises multiple step-graded layers $18s^1-18s^N$, where N is an integer representing the total number of layers, having respective lattice constants that gradually change (increase or decrease) in one direction. On one side, the buffer structure 18s forms an interface with a surface of the middle sub-cell 14s, while at an opposite side the buffer structure forms an interface with a surface of the bottom sub-cell 12s. The step-graded layers $18s^1-18s^N$ thus serve the purpose of gradually relaxing lattice strains that would otherwise

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occur between the sub-cells, confining significant dislocations to interfaces between the buffer layers 18s¹-18s^N.

5 In the example shown in Figure 2, the buffer structure 18s comprises 8 layers of GaInAs with stepwise increasing In content from 1% to 8%, and decreasing Ga content from 92% to 99%, from the bottom sub-cell 12s to the middle sub-cell 14s. Each layer 18s¹-18s^N is approximately 200 nm
10 thick, such that the buffer structure 18s has an overall thickness of approximately 1.6 μm . Those skilled in the art will appreciate that the buffer structure may have other suitable compositions and/or size depending on the application.

15 Although metamorphic TJSCs 10s may have a higher lattice mismatch between "adjacent" solar sub-cells compared to LM solar cells, the metamorphic TJSC 10s may also have a potentially more ideal sub-cell band gap combination and
20 higher efficiency than LM solar cells. Metamorphic TJSCs thus may have several advantages over LM solar cells, however further improvement may be desirable.

Figures 3 to 6 illustrate solar cell structures in
25 accordance with embodiments of the present invention. In general terms, various embodiments of the present invention propose to integrate into one structure a spectrum-splitting DBR with a multi-layer buffer structure for accommodating lattice mismatch. It is believed that
30 embodiments of the present invention may be particularly useful in metamorphic multi-junction solar cells that require compensation for a higher lattice mismatch.

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With particular reference to Figure 3, like the buffer structure 18s, a buffer structure 18t is shown that forms an interface with both a bottom sub-cell (e.g. 12s) and another sub-cell (e.g. 14s). However, the buffer structure 5 18t additionally functions as a DBR. This may be achieved by effectively converting each buffer layer 18s¹-18s^N of Figure 2 into two layers, i.e. a bilayer, each layer of the bilayer having different refractive indices. The buffer structure that additionally functions as a DBR may 10 thus hereinafter be referred to as a "hybrid" buffer/DBR structure.

It will be appreciated that any specific functions of the DBR(s) described above (such as the DBR 20) may be 15 incorporated into the design of the hybrid buffer/DBR structure 18s. For instance, the hybrid structure 18s may be configured to reflect light within a wavelengths range of 850nm to 950nm, 950 to 1050 nm, 900 to 1000nm or 900 to 1050nm.

20

In the specific example shown in Figure 3, each layer 18t¹-18t^N of the hybrid structure 18t comprises a GaInAs/GaInP bilayer, such that when the bilayers are stacked on top of each other, the hybrid structure 18t comprises alternating 25 GaInAs/GaInP layers with alternating refractive indices. This provides for the periodic structure required for the DBR. Each GaInAs has a thickness of about 83 nm, while each GaInP layer has a thickness of about 61 nm. The hybrid structure 18t thus has an overall thickness of 30 approximately 1.15 μ m. Those skilled in the art will appreciate that other suitable compositions and thicknesses may be used.

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The composition of the bilayers GaInAs and GaInP are chosen such that they have the same or substantially similar lattice constants. Thus, the hybrid structure 18t preserves the function of providing a gradual transition
5 between two solar sub-cells having mismatched lattice constants (e.g. the bottom sub-cell 12s and the middle sub-cell 14s), while also providing a periodic DBR structure.

10 Therefore, as described above, the hybrid structure 18t serves to: (a) provide a DBR that can redirect non-absorbed photons within a particular wavelength range back towards upper sub-cells in the solar cell or another solar cell; and (b) alleviate the lattice mismatch between solar
15 sub-cells of a metamorphic TJSC.

In another specific example shown in Figure 4, a hybrid structure 18u comprises 8 tri-layers 18u¹-18u^N. Each tri-layer in this example comprises either two layers of
20 GaInAs and one layer of GaInP, or two layers of GaInP and one layer of GaInAs, such that when stacked the hybrid structure 18u comprises alternating GaInP and GaInAs layers. Again, due to the different refractive indices of GaInP and GaInAs, a periodic structure is provided which
25 serves as a DBR.

In this example, each GaInP layer is about 63 nm thick, while each GaInAs layer is about 85 nm thick. The hybrid structure 18t thus has an overall thickness of
30 approximately 1.78 μm . Those skilled in the art will appreciate that other suitable compositions and thickness may be used.

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Further, in this example, at least some of the GaInP layers (i.e. the GaInP layers 26) have gradually increasing In content (from bottom to top) by 2%, and thus gradually increasing lattice constants. Additionally, some
5 of the GaInAs layers (i.e. the GaInAs layers 28) also have gradually increasing In content (from bottom to top).

As demonstrated by the plot shown in Figure 7, both hybrid structures 18t and 18u provide a degree of reflectance
10 compared to a metamorphic TJSC structure without an integrated DBR, with the (tri-layer, 8 x 3 sublayers) hybrid structure 10u performing better than the (bilayer, 8 x 2 sublayers) hybrid structure 10t.

15 In yet another example, to further increase the reflectance for spectrum splitting, an additional DBR structure may be introduced. In this regard, with particular reference to Figure 5, there is shown a schematic diagram of a hybrid buffer/DBR structure 18v
20 combined with an additional DBR 20v. Effectively, in this example, the hybrid buffer/DBR structure 18u (now 18v) shown in Figure 4 now has an additional DBR located above it. The thicknesses of the layers of the hybrid structure 18v are then re-optimised.

25

As in the example shown in Figure 4, the hybrid structure 18v comprises tri-layers $20v^1$ - $20v^N$, each tri-layer comprising either two layers of GaInAs and one layer of GaInP, or two layers of GaInP and one layer of GaInAs.
30 Accordingly, when stacked the hybrid structure 18v comprises alternating GaInP and GaInAs layers.

The additional DBR 20v comprises bilayers of GaInP/GaInAs

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such that when stacked the DBR 20v also has alternating GaInP and GaInAs layers. The DBR 20v is stacked on top of the hybrid structure 18v and provides a further means of reflecting non-absorbed photons within a particular wavelength range back towards upper solar sub-cells or another solar cell, thus potentially increasing the efficiency of the overall solar cell. In this example, the overall thickness of the hybrid structure 18v and the additional DBR 20v is approximately 4.14 μm .

10

As demonstrated by the graph shown in Figure 8, reflectance is improved with the additional DBR 20v compared to a case where no additional DBR 20v is provided.

15

In yet another example, two or more additional DBR structures may be introduced. With particular reference to Figure 6, there is shown a hybrid buffer/DBR structure 18w similar to the structure shown in Figures 4 and 5, with two DBR structures 20w and 24w, each having alternating GaInP and GaInAs layers. In this example, the overall thickness of the hybrid structure 18w and the additional DBRs 20w, 24w is approximately 6.51 μm .

25 Notably, the thickness of each hybrid tri-layer shown in Figures 4 to 6 (approximately 193-235 nm) happens to be similar to an optimum buffer step size of approximately 250 nm found experimentally for lattice-mismatched single-junction GaInAs/GaInP(buffer)/GaAs solar cells. This suggests a compatibility between optical DBRs and electronic buffer functions.

30

Optical model of a lattice-matched triple-junction solar

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cell with intermediate DBR

The state-of-the-art 1-sun terrestrial III-V on Ge TJSC is a 34.1% modified space cell. A measurement of the spectral specular reflectance of such a LM $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{Ga}_{0.99}\text{In}_{0.01}\text{As}/$ Ge TJSC was obtained using a Perkin-Elmer Lambda 1050 UV-Vis-NIR spectrophotometer with Universal Reflectance Accessory (URA) at 8° angle of incidence.

10 A reflectance peak at 900 nm is observed (see Figure 11), which is near the band edge of the $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$ middle sub-cell. This reflectance feature is consistent with an intermediate DBR located between the $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$ middle and Ge bottom sub-cells, intended to reflect at least some of the non-absorbed band edge photons back into the $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$ middle sub-cell to increase photocurrent without significant loss to the Ge sub-cell.

The inventors developed an optical model of the TJSC with DBR, such that the simulated and measured reflectance are a close match. Optical analysis software WVASE® was used to fit the modelled reflectance to the measured data, by allowing the layer thicknesses to be automatically adjusted (within sensible bounds). This TJSC has an $\text{Al}_2\text{O}_3/\text{TiO}_2$ double-layer antireflection (DLAR) coating. For the purpose of the simulation, the optical constants of the DLAR, Ge, and Al are known from published literature. The optical constants of the ternary alloys AlInP , GaInP and AlGaAs are taken from the NSM semiconductors database. For intermediate alloys, values are determined using the effective medium approximation. Linear interpolation and/or extrapolation are used for missing wavelengths. For the $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$ layer, the extinction coefficient k is

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determined from the absorption coefficient of GaAs with p-type doping $4.9 \times 10^{17} \text{ cm}^{-3}$, with a rigid 20 meV shift to lower energy due to the 1% In content. These optical constants are shown in Figure 9. Specifically, Figure 9(a) and Figure 9(b) show the complex refractive index of the top, middle, and bottom sub-cells, and the DBR layer. Figure 9(c) and Figure 9(d) show complex refractive indices for the anti-reflection coating (ARC) layers and the rear aluminium (Al) layer in the modelled lattice matched TJSC.

Figure 10 depicts a further embodiment of a lattice-matched TJSC structure 40, which provides reflectance values on par with the state of the art TJSC, as determined by the optical simulation process described above. The structure 40 includes an $\text{Al}_2\text{O}_3/\text{TiO}_2$ double-layer antireflection (DLAR) coating 42, a bottom Ge sub-cell 44, a middle sub-cell 46 comprising GaInAs, and a top sub-cell 48 comprising GaInP. The structure 40 also includes a DBR layer 50. The specific composition of the middle sub-cell 46 is $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$.

The DBR 50 in this structure 40 is adapted to reflect photons including those having a wavelength which is a spectral range not absorbed by the sub-cells 48, 46, 44. Those reflected photons, therefore, rather than boosting the photocurrent through the middle and upper sub-cells 48, 46, are reflected out of the TJSC 40, as represented by the arrow 52 in Figure 10. The outbound angle of the reflected photos will depend on the angle of incidence.

In one embodiment, the DBR 50 comprises 16 bilayers of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$, at 63nm and 72nm thicknesses,

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respectively. This DBR 50 is situated between the middle sub-cell 46 and the Ge bottom sub-cell 44.

The 16 bilayers in the DBR 50 can have the same or
5 substantially the same thickness as each other.
Realistically, the thicknesses of the layers may vary due to, e.g., variation in the deposition process.

The DBR 50 in the TJSC structure 40 provides a peak
10 reflectance at a wavelength range around 900nm, at an 8°
(see Figure 11) and also at a 45° (see Figure 12) angle of incidence (AOI). It is thus suited to spectrum splitting applications, where light in the spectral range suitable for Si cells is at least partially reflected toward an
15 adjacent, silicon solar cell. As can be seen in Figure 12, the reflectance profile 54, for the DBR 50 having the 16 $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ bilayers mentioned above, provides a peak reflectance at around 900-920 nm. However, at above 900nm, the reflectance achieved by the DBR is lower than
20 the reflectance achievable by existing dielectric filter.

Intermediate DBR for band-reflect spectrum splitting

25 As shown in the above, the intermediate DBR 50 in the LM TJSC 40 already gives a substantial 900 nm reflectance peak at 45° angle of incidence (AOI) suited to spectrum splitting applications.

30 The most preferable embodiments will be further adapted to achieve spectral splitting over a spectral band, and not just at a particular point in the spectrum or narrow range of wavelengths.

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For a latticed matched TJSC, optimal spectrum splitting to a Si cell is achieved by diverting more of the near infrared (NIR) light away from the bottom sub-cell 44, without reducing or substantially reducing the Jsc of the middle (current-limiting) sub-cell 46 (i.e., without reducing or substantially reducing the amount of photons in the middle sub-cell spectral range that are reflected back toward the middle sub-cell 46). Particularly, in some examples, photons in the entire 900 to 1050nm spectral range are the target for diversion. Ideally, the photons are reflected away from the bottom sub-cell 44 in the entire near infrared spectral range.

In some embodiments, the bilayers in the DBR are divided into two or more sets of bilayers to provide a broader reflection band. The bilayers in each set have a different bilayer thickness and hence reflectance band, compared with the bilayers in the other set. Thus, each set of bilayers will be adapted to achieve reflectance of a different spectral range.

In some instances, the DBR 50 includes 16 bilayers, which are divided into two sets of 8 bilayers, each set providing a reflectance peak at a different spectral range. For example, Figure 13 is a plot of simulated spectral reflectance as a function of wavelength, of the general TJSC structure shown in Figure 10, but with the DBR 50 comprising two sets of 8 Al_{0.2}Ga_{0.8}As/Al_{0.8}Ga_{0.2}As bilayers, in which each bilayer is provided at a thickness of 63 nm and 72 nm, respectively. The reflectance profile 54, compared to the reflectance profile 52 of the single set of 16 bilayers DBR, exhibit more reflectance peaks in

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the target range of 900–1050 nm. However at least some of these peaks can be observed to have a lower reflectance.

However, with a reduced number of DBR bilayers (from 16 to 5 8) covering the spectral range between 850–900 nm, this approach undermines the benefit of boosting the middle sub-cell photocurrent (see Table 1, where the photocurrent of the middle sub-cell is reduced compared to the prior art TJSC).

10

Thus, more preferred embodiments are adapted to retain the DBR's function of boosting sub-cell photocurrent(s), whilst broadening the spectral reflectance range – that is, the spectral range of the light which will be 15 reflected at an angle away from the TJSC structure where the DBR 50 is located – to include wavelengths in ranges not absorbed by the TJSC sub-cells.

Figure 14 depicts a plot of simulated spectral reflectance 20 as a function of wavelength, of the TJSC structure generally shown in Figure 10, with the DBR 50 comprising 32 Al_{0.2}Ga_{0.8}As / Al_{0.8}Ga_{0.2}As bilayers. The reflectance profile 56 of the resulting TJSC is shown in pink. The 32 bilayers include the 16 bilayers mentioned in respect of 25 Figure 12, and 16 additional bilayers. Therefore, the 32 bilayers in the DBR 50 are dividable into two different sets. The 16 bilayers in the first set has a first thickness of 135 nm (for each bilayer structure). The 16 bilayers in the second set has a second thickness of 158 30 (76+82)nm. The bilayers of the same thicknesses (from the same set) are shown to be provided in one stack (i.e. adjacent each other), rather than being interlaced with bilayers of different thicknesses (i.e. from the other

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set). However, the bilayers belonging to one set may be interlaced with bilayers belong to the other set.

The 16 additional (i.e. second set of) bilayers are
5 provided with suitable thicknesses such that the reflectance for the additional 16-bilayer set is shifted to longer wavelengths to avoid the atmospheric absorption band around 950 nm, where little energy is harvestable from photons at these wavelengths compared to other
10 wavelengths. From the reflectance profile 56, it can be observed that one peak is located at around 900nm, and another peak reflectance range is provided at around 1000 nm. The shift of the peak reflectance range to the "red" (i.e. longer) end of the wavelength spectrum is caused by
15 thicker bilayers. Typically, a 1nm increase in the thickness of the "period" (i.e. bilayer or trilayer) in the periodic structure can result in a shift in the wavelength of peak reflectance of about 2 to 5 nm.

20 In a further embodiment, the DBR 50 includes 48 bilayers - that is, triple the number of the original number of the bilayers shown in respect of Figure 13 and Figure 14.

The additional sets of DBR bilayers progressively enhance
25 the reflectance for spectrum splitting compared with the embodiment with only one set (16, in this example) of bilayers. In one embodiment, the thicknesses of the layers in the initial set of bilayers remain the same, but the bilayers in the second set each include $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$
30 / $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ layers at 69nm and 79nm respectively, and the bilayers in the third set each include $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ / $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ at 76nm and 87nm, respectively.

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Figure 15 depicts a plot of simulated spectral reflectance as a function of wavelength, of the TJSC structure generally shown in Figure 10 and incorporating the above mentioned DBR 50, comprising 48 Al_{0.2}Ga_{0.8}As / Al_{0.8}Ga_{0.2}As bilayers. The 48 bilayers include three sets of 16 bilayers, where bilayers in each set have different thicknesses to bilayers in the other sets. Figure 15 shows that at this configuration, the reflectance profile 58 of the resulting TJSC is similar in shape and spectral position compared to the reflectance profile 60 of a traditional TJSC with discrete dielectric layers. Thus, the LM TJSC with intermediate DBR can achieve a comparable performance to the traditional TJSC structure with the discrete dielectric filter.

It would be appreciated that more sets of DBR bilayers, at different bilayer thicknesses than those in the other sets, will further widen the reflected spectral range. However this comes at a trade off in the increase of manufacturing complexity and cost.

Thus, as a general principle, reflectance in the desired wavelength range can be further increased by using more Bragg layers of the same composition (but at more sets of different bilayer thicknesses to fine tune the reflectance profile), and/or different alloy compositions with larger refractive index contrast, subject of course to practical and economic constraints.

From the above, the skilled person will understand that the effect of increasing the number of bilayers in the same set (i.e. same bilayer thicknesses) is a potential increase in the peak reflectance.

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Photocurrent density calculation

In one method, the photocurrent density J_i of each sub-cell is calculated according to the equation

$$J_i = q \int EQE_i(\lambda) \cdot \frac{E_{AM1.5D}(\lambda)}{hc/\lambda} d\lambda,$$

5 where q is the electron charge, $EQE_i(\lambda)$ is the external quantum efficiency of the i^{th} sub-cell, $E_{AM1.5D}(\lambda)$ is the spectral irradiance of the incident solar spectrum (here assumed to be ASTM G173-03 AM1.5D), h is the Plank
10 constant, c is the speed of light, and λ is the wavelength.

For each sub-cell, it is assumed that the $EQE(\lambda)$ is equal to the absorption in that layer, calculated using the TJSC
15 optical model described above, and the transfer matrix method (e.g. described by Petterson *et al* in "Modeling photocurrent action spectra of photovoltaic devices based on organic thin films", Journal of Applied Physics, 1999. 86(1): p. 487-496.

20 For the top and middle sub-cells, the assumption of 100% collection efficiency is reasonable. However, for the Ge (bottom) sub-cell, to account for a finite diffusion length, in the modelling an effective sub-cell layer
25 thickness is used so that the modelled long wavelength EQE corresponds to the 'typical EQE ' data.

The sub-cell photocurrent densities of the LM TJSC, calculated as mentioned above, for the various device
30 structures, are shown in Table 1.

Table 1. Calculated subcell photocurrent densities of a LM TJSC with various intermediate DBR designs (for 45° AOI).

Device structure	J_{sc} top subcell (mA/cm ²)	J_{sc} middle subcell (mA/cm ²)	J_{sc} bottom subcell (mA/cm ²)
Original TJSC (standard 1×16 bilayer DBR)	13.8	12.7	18.6
TJSC with spectrum splitting DBR (2×8 bilayers)	13.8	12.2	16.4
TJSC with spectrum splitting DBR (2×16 bilayers)	13.8	12.7	14.9
TJSC with spectrum splitting DBR (3×16 bilayers)	13.8	12.7	12.8

The more preferred embodiments of LM TJSC with intermediate DBR layers, have the desired effect of diverting photons away from the Ge bottom sub-cell without detriment to the top or (current-limiting) middle sub-cells.

As can be seen from table 1, the middle and bottom sub-cells are substantially current matched in the embodiment where three sets of 16 bilayers are provided in the DBR.

The current densities and efficiencies of TJSC structures incorporating the different DBR designs as shown in Figures 12 to 15 are modelled using Solcore, a Python-based integrated optical and electrical modelling framework for solar cells. The optical part of the simulations, calculating the reflected power and depth-dependent absorption/generation rate, was carried out using the built-in transfer matrix method (TMM) optical model, using the same optical constants data which were mentioned above, for the fitting of the reflectance measurements.

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The external quantum efficiency (EQE) and light current-voltage (IV) characteristics were calculated using the depletion approximation as implemented in Solcore.

5 The EQE and efficiencies calculated for the TJSCs for normal incidence matched well with measured values provided by the manufacturer when 5% shading loss is assumed.

10 To simulate the performance of an integrated concentrator photovoltaic (CPV) receiver comprising the LM TJSC and a Si cell (e.g. see Figure 21), the reflectance and light IV characteristics of the different TJSC designs were calculated assuming an incident AM1.5D spectrum
15 concentrated 800× incident at 45° AOI on the TJSC. Light reflected from the TJSC is incident normally on the Si cell, which is modelled on an Amonix concentrator cell.

As seen from Table 1, amongst the specific examples
20 discussed in relation to Figures 13, 14, and 15, the 3×16 bilayer design comes closest to current matching conditions, but leaves a sensible margin above the limiting current, to avoid the Ge sub-cell excessively reducing the fill factor for the overall solar cell.

25

Figure 16 shows the impact on the external quantum efficiency (EQE) of changing from the prior art LM TJSC at 0° AOI (Figure 16a) to a spectrum-splitting receiver with LM TJSC at a 45° AOI plus a Si cell (thus a "4-junction"
30 arrangement) to capture the reflected light (Figure 16b). The EQE profiles 62, 64, 66, 68 are obtained from EQE data for the top sub-cell, the middle sub-cell, the bottom sub-cell in the TJSC, and the silicon solar cell receiving the

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photons reflected from the LM TJSC.

From Figure 16a and Figure 16b, it can be seen that the EQE responses 62, 64 of the top and middle sub-cells are not substantially affected. The bottom sub-cell response 66 shows that the bottom sub-cell in the prior art exhibits a low efficiency at around 900nm. With the invention, this spectral range is now captured by the silicon cell which produces a higher EQE. Although the bottom sub-cell efficiency response 66 is somewhat depressed for a portion of the spectral range, it can be seen in Figure 16b that this is compensated by the efficiency measured from the silicon solar cell.

Design of a spectrum-splitting DBR for metamorphic triple-junction solar cells

As already mentioned above (e.g. see Figure 2), the invention can provide spectrum splitting in metamorphic (MM) TJSCs, by including intermediate DBR of particular configurations.

MM TJSCs have a more ideal sub-cell bandgap combination and higher efficiency than LM TJSCs. A multilayer buffer structure is an essential part of MM TJSCs to overcome the high lattice mismatch between the Ge substrate (i.e. bottom sub-cell) and the two upper sub-cells.

The buffer used in MM TJSCs typically comprises several step-graded layers with increasing lattice constant, thereby relaxing lattice strains and confining dislocations to buffer layer interfaces. For example, the buffer in a 41% efficient MM $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}/\text{Ge}$

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TJSC has a total thickness of 1.6 μm , consisting of eight 200-nm thick GaInAs layers with stepwise increasing indium content from 1% to (an overshooting) 20%.

5 Another prior art TJSC structure is the so-called 'MM-lite' TJSC generally shown in Figure 2. It includes a $\text{Ga}_{0.44}\text{In}_{0.56}\text{P}/\text{Ga}_{0.92}\text{In}_{0.08}\text{As}/\text{Ge}$ structure, i.e. a $\text{Ga}_{0.44}\text{In}_{0.56}\text{P}$ top sub-cell, a $\text{Ga}_{0.92}\text{In}_{0.08}\text{As}$ middle sub-cell, and a Ge bottom sub-cell. Figure 2 shows that the structure also
10 has buffer comprising eight GaInAs layers with stepwise increasing indium content from 1% to 8% (no overshoot).

As mentioned above, in accordance with the present invention, the MM TJSC structure can be further modified,
15 where the 8-step buffer layer of GaInAs is replaced by a GaInAs/GaInP bilayer (see Figure 3), or into trilayers of GaInAs and GaInP (see Figure 4). These layers can further be tuned (by changing their thicknesses and/or material composition) so that the reflected range include
20 wavelengths which are not absorbed by the sub-cells, and thus reflected toward one or more other solar cells (e.g. silicon solar cell) which are adapted to absorb those wavelengths.

25 One embodiment includes an MM TJSC with an intermediate DBR, where the DBR includes 2 sets of 16 bilayers plus a third set of 8 trilayers

As described, the 8-step buffer 18s in the MM-lite TJSC is
30 modified to additionally function as a (spectrum-splitting) DBR. In the examples shown in Figure 3 and Figure 17, this is done by converting each GaInAs buffer layer into a GaInAs/GaInP bilayer. IN the examples shown

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in Figure 4 and Figure 18, this is done by converting each GaInAs buffer layer into trilayers of GaInAs and GaInP.

The example structures shown in Figure 17 and Figure 18
5 use the same alloys with the same graded compositions, as those shown in Figure 3 and Figure 4. However, the structures in Figure 17 and Figure 18 have different layer thicknesses, because the thicknesses of the layers were re-optimised using more accurate optical constants for the
10 semiconducting alloys used in the TJSC.

In Figure 17, each "period" in the periodic structure (i.e. bilayer) has a 59nm layer of GaInP and an 88 nm layer of GaInAs. Each periodic structure thus has a
15 thickness of 147nm, compared with 144 nm for the period structure shown in Figure 3.

In Figure 18, each "period" in the periodic structure (i.e. trilayer) has two 66nm layers of GaInP, and an 83 nm
20 layer of GaInAs or two 83nm layers of GaInAs and a 66 nm layer of GaInP. Each "period" thus has a thickness of 215 nm (or 235 nm), compared with 211 nm (or 233nm) for the period structure shown in Figure 3.

25 The novel BDR designs (one shown in Figures 3 and 17; one shown in Figures 4 and 18) preserve the original step-wise lattice matching, whilst introducing the advantage of an intermediate DBR allowing improved efficiency and radiation tolerance (relevant to space cells) and the
30 potential for spectrum splitting.

However, as in the case for an MM TJSC incorporating the DBR structure discussed in relation to Figure 3 or Figure

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3, the reflectance of achieved by incorporating the DBR/buffer of Figure 17 or Figure 18 is only moderately effective for spectrum splitting purposes, with the 8-trilayer case being the most promising of the two.

5

In the aforementioned novel DBR, the lattice constants of the DBR layers generally increase in one direction along the DBR. However, in some particular embodiments, there can be a decrease in the lattice constants from at least one of the step-graded layer to next adjacent step-graded layer in the DBR. These decreases are "reverse-steps" in the otherwise monotonic increase.

The insertion of 'reverse-step' buffer layers (buffers between which there is a decrease in the lattice constants) introduces tensile strain in the common compressive step-graded buffer structure, and significantly reduces the threading dislocation density. The reflectance of these tensile/compressive structures is quite similar to the compressive step-graded buffer structures (with monotonically increasing lattice constants).

Figure 19 and Figure 20 are alternative BDR structures to those shown in Figure 17 and Figure 18. They have the same structures (i.e. type and compositions of alloys) as those shown in Figure 5 and Figure 6, but with different thicknesses of the bilayers or trilayers. Again, the differences in the thicknesses are due to the re-optimisation using a more accurate (i.e. less relaxed) set of optical constants.

In the structure shown in Figure 19, the DBR includes a

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set of 16 bilayers of 54nm GaInP and 91nm GaInAs, and a set of 8 trilayers (two 83nm layers of GaInAs and a 69 layer of GaInP; alternating with two 69nm layers of GaInP and an 83nm layer of GaInAs) with stepped compositions. In
5 the structure shown in Figure 20, the DBR includes three sets of periodic structures. The first set includes 16 bilayers (a 64 nm layer of GaInP and a 83 nm layer of GaInAs). The second set also includes 16 bilayers, each comprising an 81nm layer of GaInP, and a 74 nm layer of
10 GaInAs. The third set includes 8 trilayers with stepped composition, alternating between two 52 nm layers of GaInP and an 89 nm layer of GaInAs, and two 89 layers of GaInAs and a 52 layer of GaInP.

15 However, the same structures, when provided with the thicknesses shown in Figures 3 to 6, still achieve a workable reflectance in the desired wavelength range.

With the additional DBR structures (using the thicknesses
20 shown in Figures 17 to 20), the photocurrent densities of the Ge bottom sub-cell are progressively reduced due to the reflecting/diverting of the excess photocurrent, while the top and middle sub-cells are not affected. There is thus a trade off between the bottom sub-cell current
25 density, and the width of the reflected band as achieved by the use of a combination of different DBRs.

The photocurrent densities of the top, middle and bottom sub-cells of the MM-lite TJSC with intermediate DBR/buffer
30 are shown in Table 2. The calculations for the photocurrent densities are the same as those described earlier in this specification.

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The '2×16 bilayer DBR + 8-trilayer DBR/buffer' (see Figure 6 and Figure 20) structure provides desirable spectrum splitting between the MM-lite TJSC and a Si solar cell.

- 5 Specific parameters of the DBR can be determined by the skilled person on the basis of the receiver conversion efficiencies (rather than sub-cell current matching).

Table 2. Calculated subcell photocurrent densities of an MM-lite TJSC with optimized DBR/buffer + additional DBR structure (for 45° AOI).

Device structure	J_{sc} top subcell (mA/cm ²)	J_{sc} middle subcell (mA/cm ²)	J_{sc} bottom subcell (mA/cm ²)
Original TJSC (DLAR, no DBR)	15.0	13.3	17.6
TJSC with spectrum splitting DBR (1×16-bilayer DBR + 8-trilayer DBR/buffer)	15.0	13.3	14.6
TJSC with spectrum splitting DBR (2×16-bilayer DBR + 8-trilayer DBR/buffer)	15.0	13.3	13.4

10

Angle of incidence response

The TJSC structure with the DBR spectral band reflector can be incorporated in the same system with another photo-
 15 voltaic structure. For example, Figure 21 shows a central receiver concentrated photovoltaic (CPV) power tower system, comprising centralised power tower arrangement. In the example arrangement, a field of heliostats 70 concentrate the sunlight to a single flat 1-m² array of
 20 TJSCs 72 atop a mast 74. The TJSC includes the DBR for spectral band reflection in accordance with the present invention, to provide spectrum splitting from the TJ array to an additional array of Si cells 79.

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The inset in Figure 21 depicts a ray-trace diagram of one possible (band-reflect) spectrum-splitting receiver. A secondary optical element 76 is provided to further direct and/or concentrate the light from the heliostats 70 towards the TJSC 72. In this example the secondary optical element 76 is a hollow reflective truncated pyramid. It has an "exit" 78 from which the concentrated light becomes incident upon the TJSC 72. The location of the exit 78 is defined by the location of the 1m² TJSC array 72 in the baseline receiver, arranged to define an angle of incidence. A silicon solar cell or solar cell array 79 is located at an angle to the TJSC array 72, adapted to receive the light reflected from the TJSC array 72.

In the traditional approach, there can be a broad distribution of angles of incidence (AOIs) on the light receiving TJSC, which could limit the benefits of spectrum splitting using a dielectric filter (e.g. provided as a cover glass) due to the sensitivity of the dielectric filter to the AOI. In contrast, the present invention exhibits a greatly reduced sensitivity to AOI.

Figure 22 shows the simulated response of the modified TJSC structure to the angle of incidence of the incoming light. As can be seen in the AOI response 80 for dielectric filters, for AOI increasing from 0 to 80°, the cut-on and cut-off wavelength of the dielectric filter shifted by a relatively large 160 nm and 211 nm respectively. In contrast, as can be seen by the AOI responses 82, 84, the TJSC structure with the DBR filter exhibits much smaller shifts of only 20 nm and 45 nm for LM TJSC, and 37 nm and 41 nm for MM TJSC, respectively.

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The DBR filter therefore has a significant advantage over the dielectric filter, especially when the incident light has a broad distribution of AOIs.

5 As described, the current invention involves the modification of the internal distributed Bragg reflector in the lattice-matched triple-junction solar cell so that it acts as a band-reflect filter to divert otherwise wasted light (nominally in the 900-1050 nm range) to a Si
10 solar cell. The diversion of this specific wavelength range being diverted to a silicon cell can be seen in Figure 16(a) and Figure 16(b), for the LM TJSC example. Figure 16(b), in particular, demonstrate the external quantum efficiency (EQE) 68 measured from the silicon cell
15 to which the reflected light is directed.

A potentially cost-effective approach is also proposed to enhance the performance of metamorphic triple-junction solar cells by integrating a distributed Bragg reflector
20 into the conventional buffer layer structure.

The proposed structure reveals a promising way to achieve higher efficiency and more radiation tolerant metamorphic devices, with the option of spectrum splitting to separate
25 devices. An intermediate Bragg reflector could also be implemented in other III-V device structures including single and double junction cells to effect spectrum splitting to another, not necessarily Si, solar cell. A major advantage of the Bragg reflector approach to
30 spectrum splitting is the significantly reduced angular dependence compared to dielectric filters.

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The integrated DBR approach described above can be implemented with little additional cost during manufacture of the TJSC, in contrast to the use of discrete dielectric filters.

5

It will be understood to persons skilled in the art of the invention that many modifications may be made without departing from the spirit and scope of the invention.

10 For example, although numerous examples of thicknesses of semiconductor layers, material types and compositions are described above, such examples are not limiting and a person skilled in the art will understand that many variations are possible without departing from the scope
15 of the claims. For example, instead of the bottom sub-cell comprising Ge material, it may comprise another semiconductor material, such as GaAs, or InP. The multi-junction solar cells can have different material structures. For example, the multijunction solar cells can
20 be provided on a GaAs or an InP substrate, e.g. GaInPAs/GaInPAs/GaInAs on an InP wafer.

As another example, in further embodiments where the intermediate DBR is adapted to reflect at least some of
25 the photons in a spectral band to another solar cell, the other solar cell can be a type different than a silicon solar cell.

Different thicknesses than those mentioned above or included in the drawings may be used - depending on the
30 application and the desired reflectance profile. They can be in the range from approximately 50nm to approximately 100nm, or from 10nm to 200nm.

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In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as
5 "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

10 It is to be understood that, if any prior art publication is referred to herein, such reference does not constitute an admission that the publication forms a part of the common general knowledge in the art, in Australia or any other country.

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Claims

1. A solar cell structure comprising:
a first material component comprising a substrate and
5 having a surface;
a layered structure forming an interface with the
surface of the first material component; and
a second material component comprising at least one
solar cell component arranged to absorb a portion of light
10 within a first wavelength range, the second material
component having a surface at an interface with the
layered structure;
wherein the layered structure comprises a distributed
Bragg reflector (DBR) that is formed from a stack of
15 single layers having selected thicknesses and refractive
indices, the DBR being configured to reflect light within
a second wavelength range.
2. The solar cell structure of claim 1, the second
20 material component having, at the surface at the interface
to the layered structure, a lattice constant that differs
from a lattice constant of the first material at the
interface to the layered structure, wherein the DBR is
part of or comprises a buffer for the solar cell
25 structure.
3. The solar cell structure of claim 1 or claim 2, the
second wavelength range is 850 nm to 950 nm, 950 to 1050
nm, 900 to 1000 nm or 900 to 1050 nm.
- 30 4. The solar cell structure of any one of claims 1 to 3,
wherein the second wavelength range at least partially
overlaps with the first wavelength.

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5. The solar cell structure of any one of claims 1 to 3, wherein the second wavelength range does not overlap with the first wavelength range.

5

6. The solar cell structure of any one of the preceding claims, wherein the DBR is configured to reflect, dependent on an angle of incidence of incoming light, light back towards the at least one solar cell component
10 of the second material component and/or out of the solar cell structure for absorption by another solar structure.

7. The solar cell structure of claim 6, wherein the other solar structure is silicon based, comprising a silicon
15 solar cell, or a stack of two or more solar cells including a silicon cell.

8. The solar cell structure of any one of the preceding claims wherein the layered structure comprises a periodic
20 structure.

9. The solar cell of claim 8, wherein the periodic structure comprises multiple single layers, arranged so that single layers of two or more types of different
25 materials alternate in the periodic structure.

10. The solar cell of claim 9, the single layers being step-graded layers each having a lattice constant, wherein the lattice constants of the step-graded layers overall
30 increases in one direction along the periodic structure.

11. The solar cell structure of claim 10, wherein there is a decrease in the lattice constants from at least one of

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the step-graded layer to next adjacent step-graded layer in the one direction along the periodic structure, but the lattice constants overall increase in the direction along the periodic structure.

5

12. The solar cell structure of any one of claim 9 to 11 wherein a composition of each type of material of the layered structure gradually changes in one direction along the stack of layers.

13. The solar cell structure of any one of claims 9 to 12, wherein a first type of material of the layered structure comprises GaInAs, and a second type of material of the layered structure comprises GaInP.

14. The solar cell structure of claim 13, wherein the first type of material of the layered structure comprises $Ga_xIn_{1-x}As$ and the second type of material of the layered structure comprises $Ga_yIn_{1-y}P$ with x and y gradually decreasing in one direction along the stack of layers.

15. The solar cell structure of any one of claims 9 to 14 wherein the layered structure comprises three or more types of materials, which are ordered in periods comprising three or more respective single layers.

16. The solar cell structure of any one of the preceding claims, wherein the single layers of the buffer layer structure have a thickness generally ranging from approximately 50 nm to approximately 100 nm.

17. The solar cell structure of any one of the preceding

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claims wherein the first material component comprises at least one further solar cell component and which is in use positioned below the buffer layer structure and above the substrate.

5

18. The solar cell structure of claim 17 wherein, the at least one further solar cell component comprises germanium, GaAs, or InP.

10 19. The solar cell structure of any one of the preceding claims, comprising at least two solar cell components that are located within the second material component, and in use located above the layered structure, such that in use the DBR reflects a portion of light that travelled through
15 the at least two solar cell components back towards the at least two solar cell components for absorption by at least one of the at least two solar cell components.

20 20. The solar cell structure of any one of the preceding claims, comprising a series of solar cell components, which are ordered such that incoming light travels through a succession of the solar cell components having decreasing bandgap energies.

25 21. The solar cell structure of claim 20, wherein the layered structure is located between two of the series of the solar cell components, the second wavelength range partially overlaps or does not overlap with a wavelength range within which at least one of the solar cell
30 components, which is in use positioned above the layered structure, absorbs light.

22. The solar cell structure of claim 20, wherein the

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second wavelength range does not overlap with another wavelength range within which at least one of the solar cell components, which is in use positioned above the buffer layer structure, absorbs light.

5

23. The solar cell structure of any one of the preceding claims, wherein the first material component comprises more than one solar cell component comprising GaAs, GaInAs, GaInP or another suitable material, and which are
10 ordered such that incoming light travels through a succession of the solar cells components within the first material component with decreasing bandgap energies.

24. The solar cell structure of claim 23 wherein the solar
15 cell structure comprises a GaInP-based solar cell component, a GaInAs-based solar cell component, and a Ge-based solar cell component, and wherein the layered structure is positioned between the GaInAs-based solar cell component and the Ge-based solar cell component.

20

25. The solar cell structure of any one of the preceding claims, comprising at least one further DBR, configured to reflect light within at least a third wavelength range.

25 26. The solar cell structure of claim 25, wherein the third wavelength range is different from the second wavelength range.

27. The solar cell structure of claim 25 or claim 26,
30 wherein the at least one further DBR is positioned in the proximity of the layered structure.

28. The solar cell structure of any one of claims 25 or

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27, wherein the second material component comprises the at least one further DBR and wherein the at least one further DBR forms the interface with layered structure.

5 29. The solar cell structure of any one of claims 25 to 27, wherein the first material component comprises the at least one further DBR and wherein the at least one further DBR forms the interface with the layered structure.

10 30. The solar cell structure of any one of claims 25 to 29 wherein the at least one further DBR comprises a plurality of stacked bilayers or trilayers.

31. The solar cell structure of any one of claims 25 to
15 30, wherein the DBR and at least one further DBR are each adapted to provide peak reflectance at different wavelengths.

32. A solar arrangement, including a first solar cell
20 structure of any one of claims 1 to 31, and a second solar structure which is adapted to receive light reflected by the first solar cell structure.

33. The solar arrangement of claim 32, wherein the second
25 solar structure includes at least one silicon solar cell.

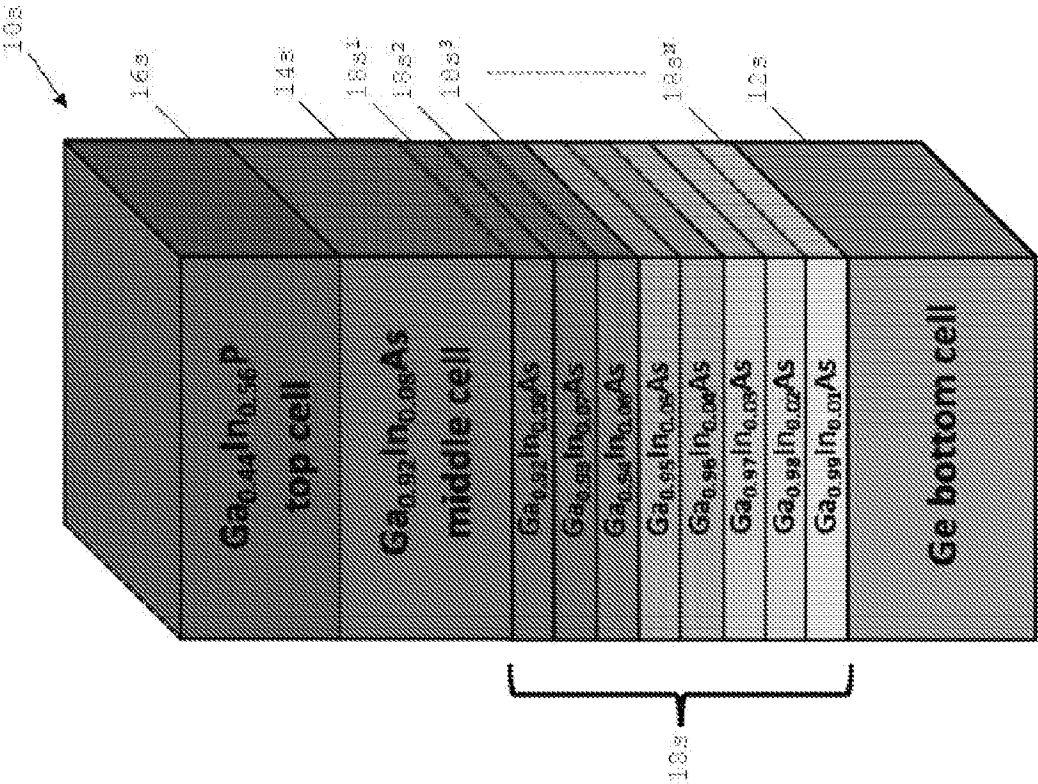


Figure 2

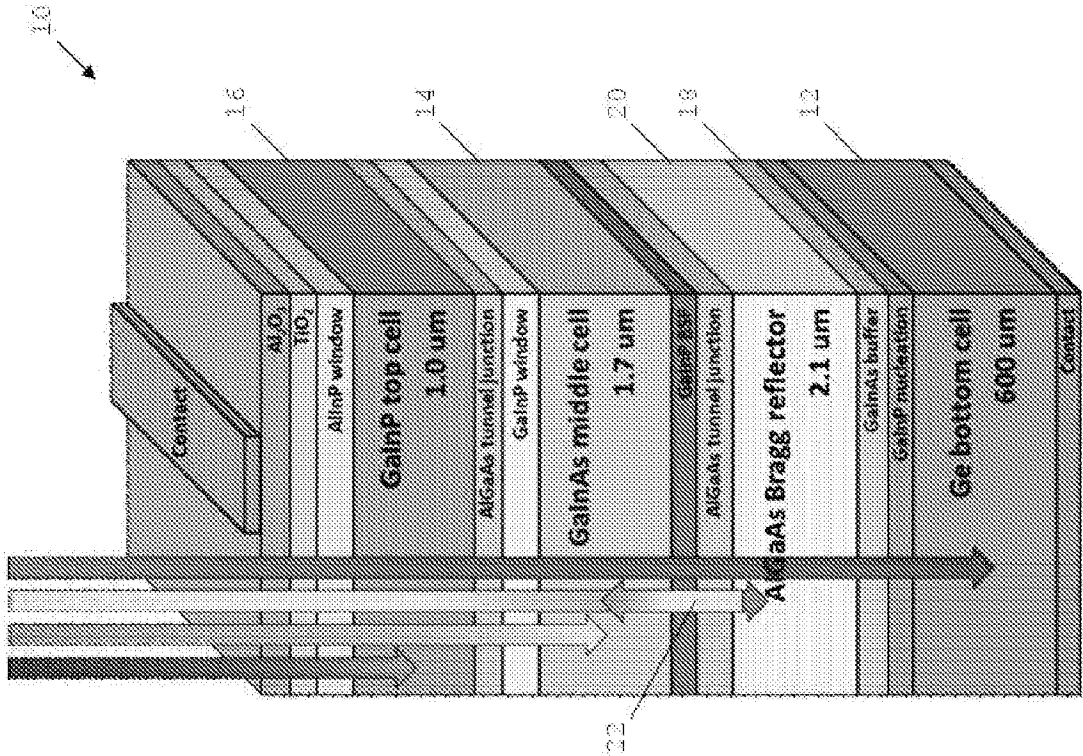


Figure 1

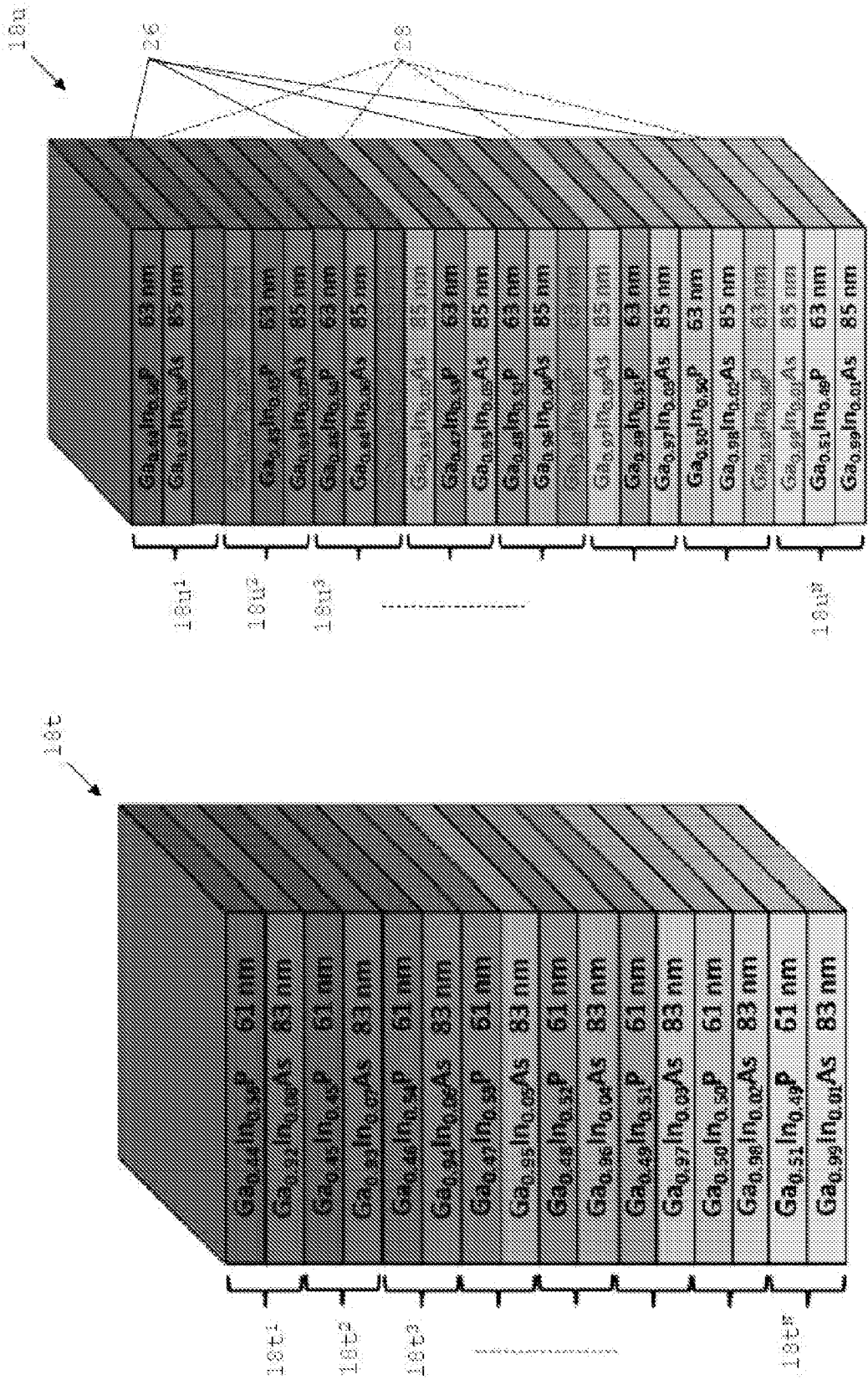
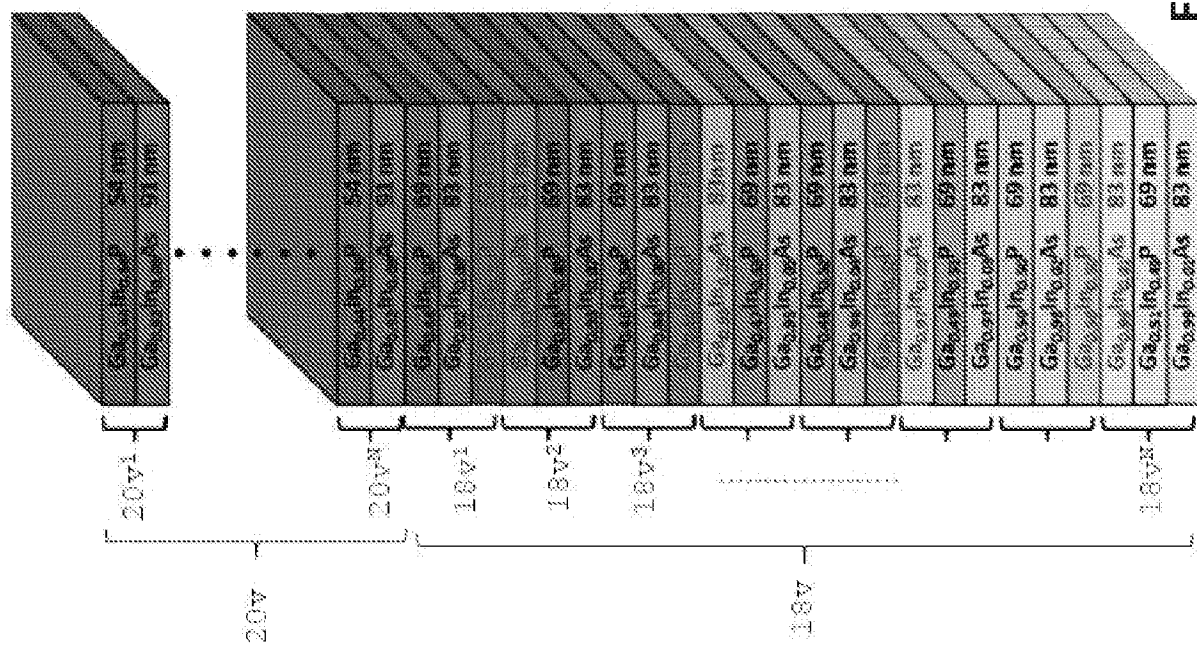
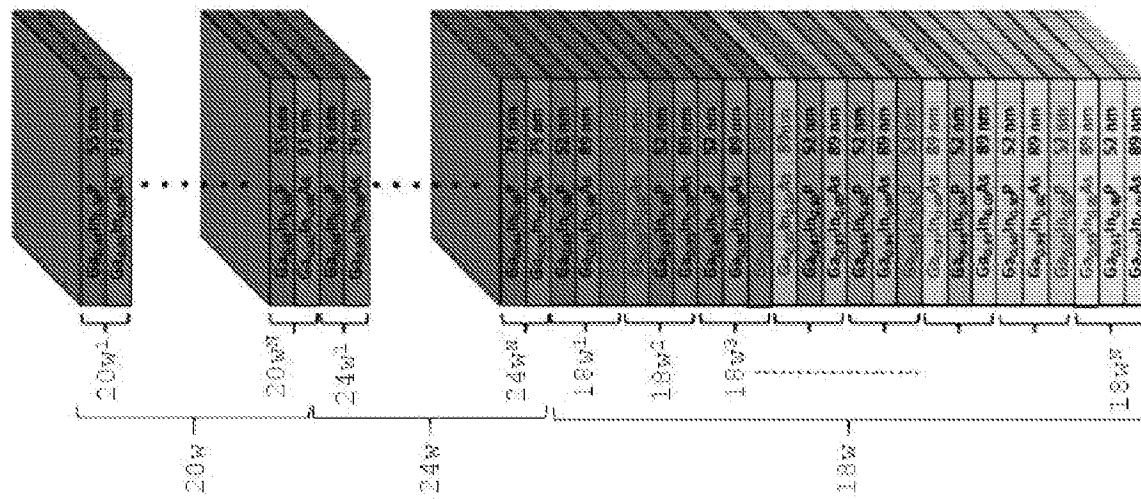


Figure 4

Figure 3



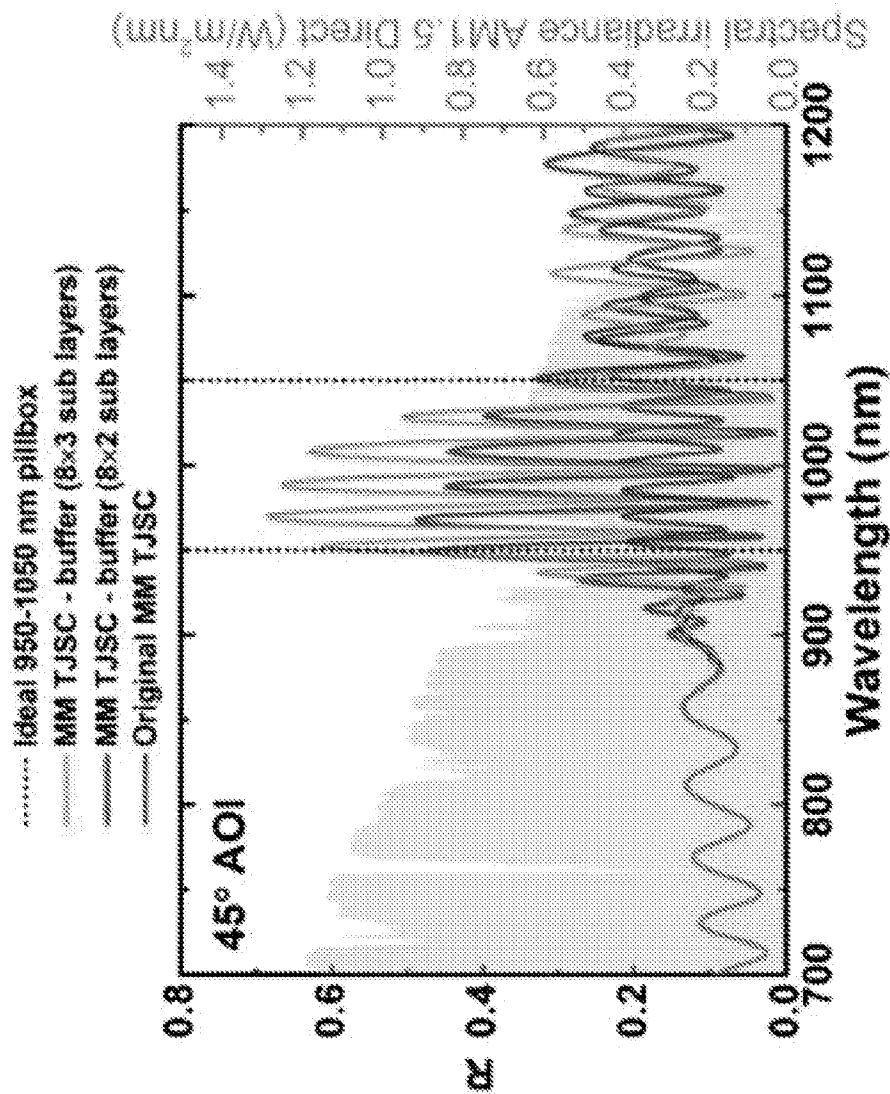


Figure 7

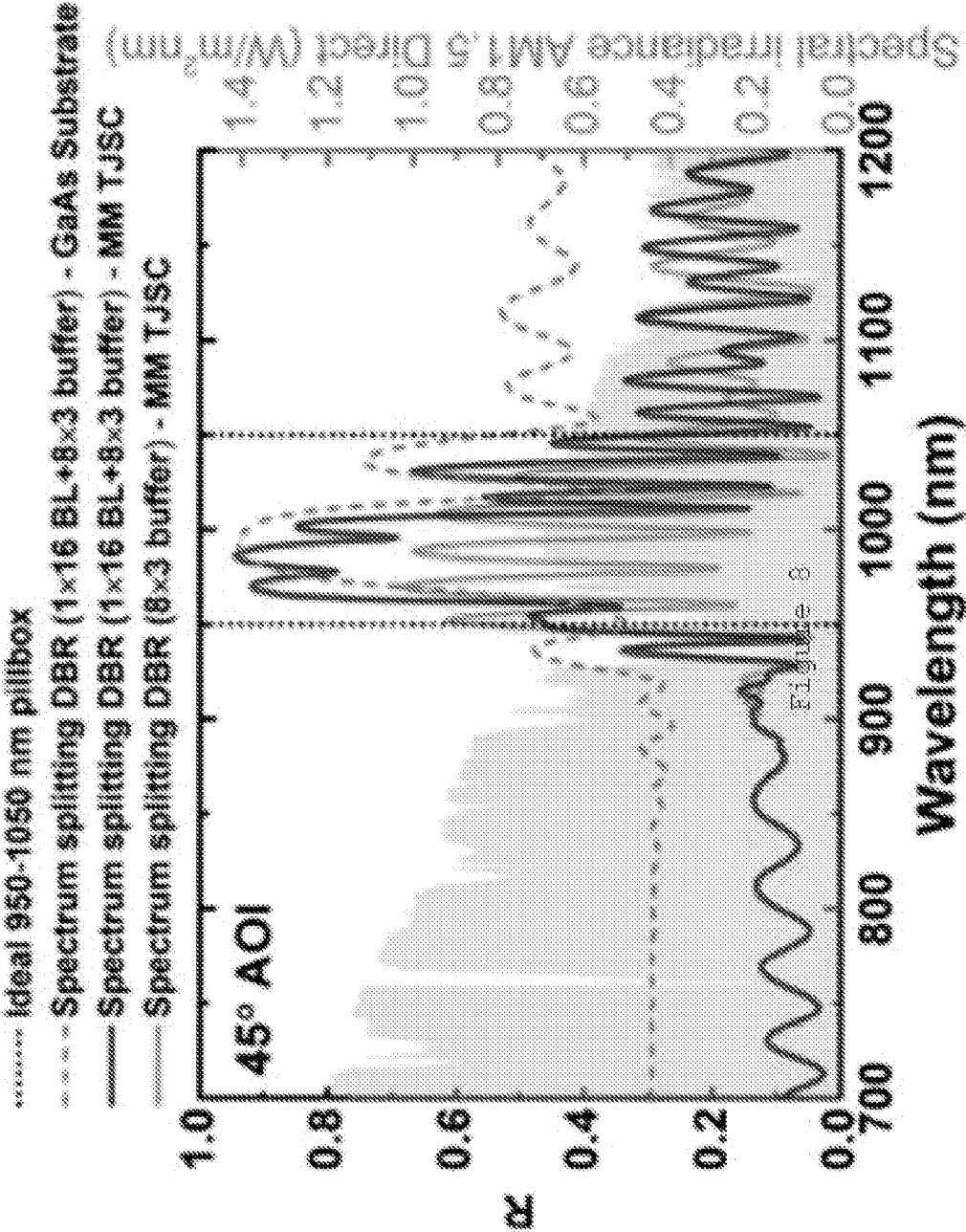


Figure 8

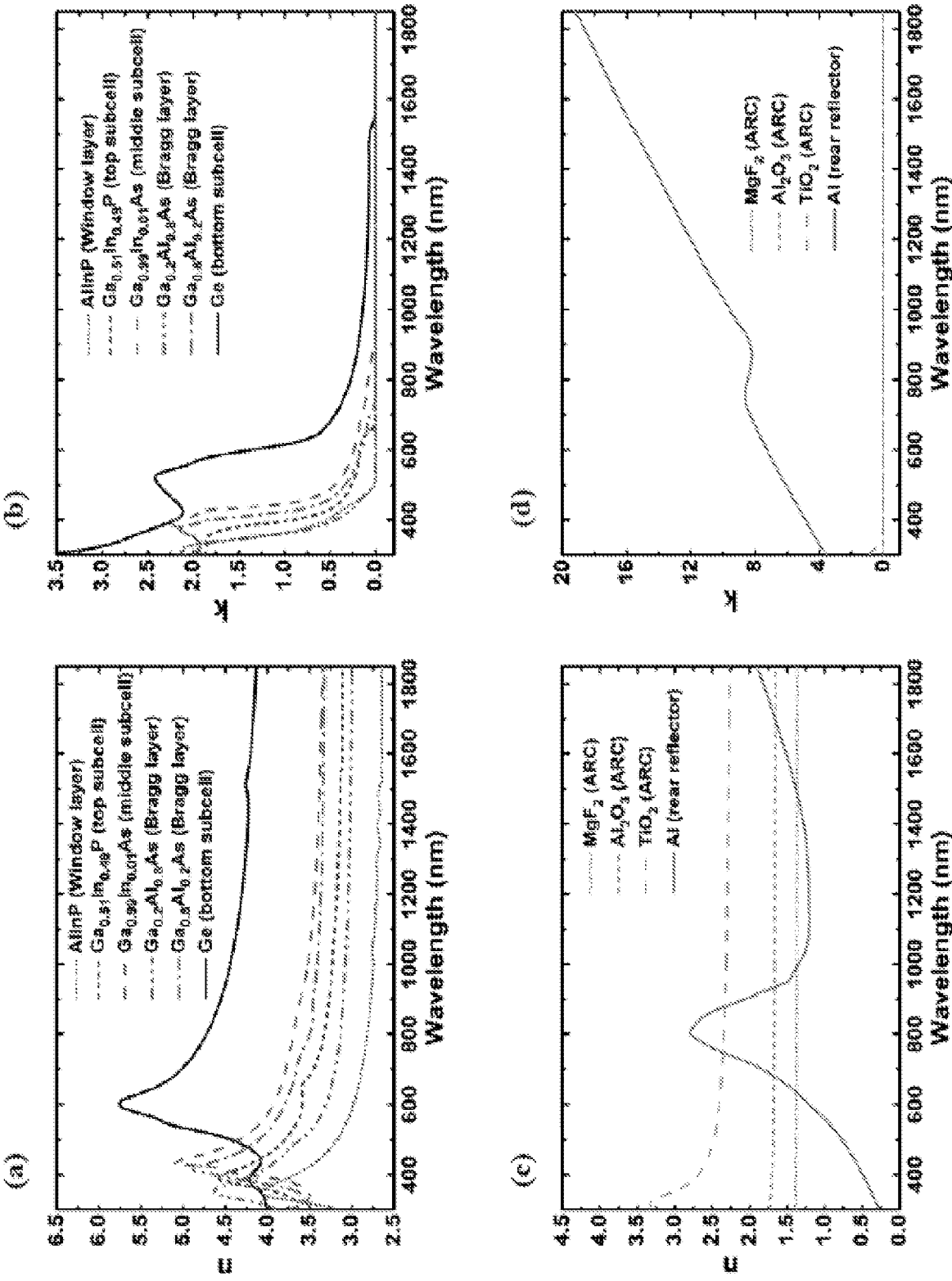


Figure 9

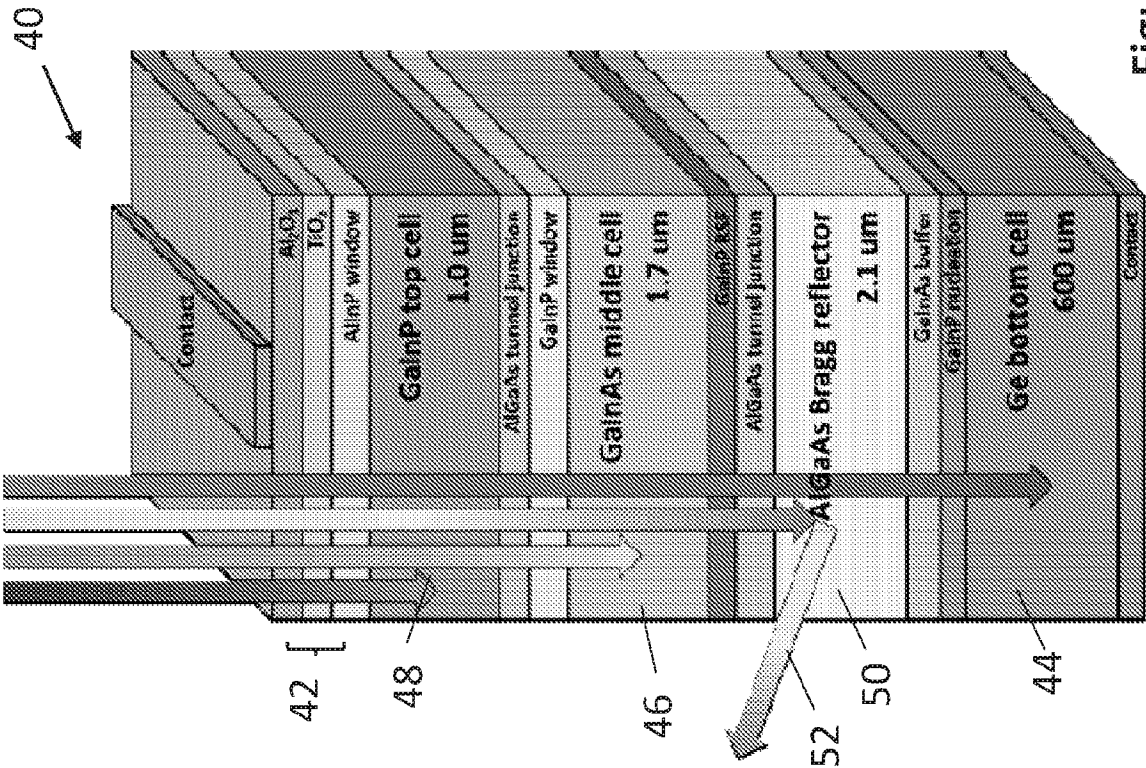


Figure 10

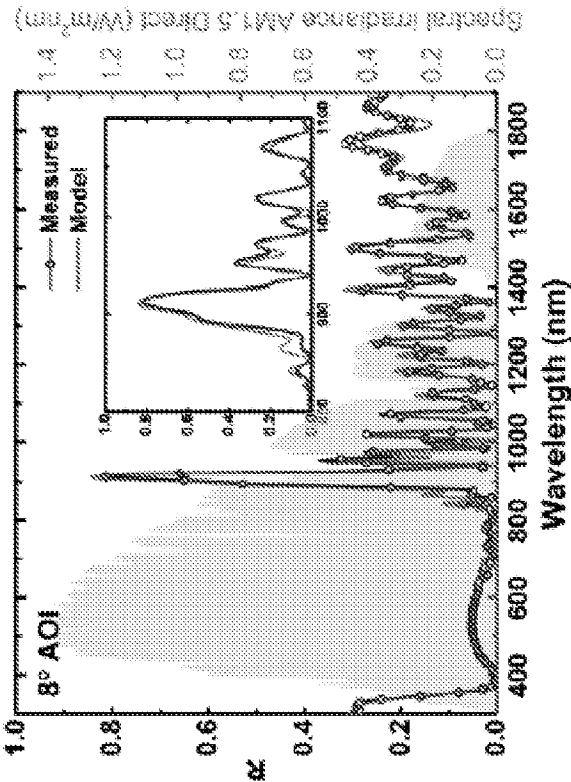


Figure 11

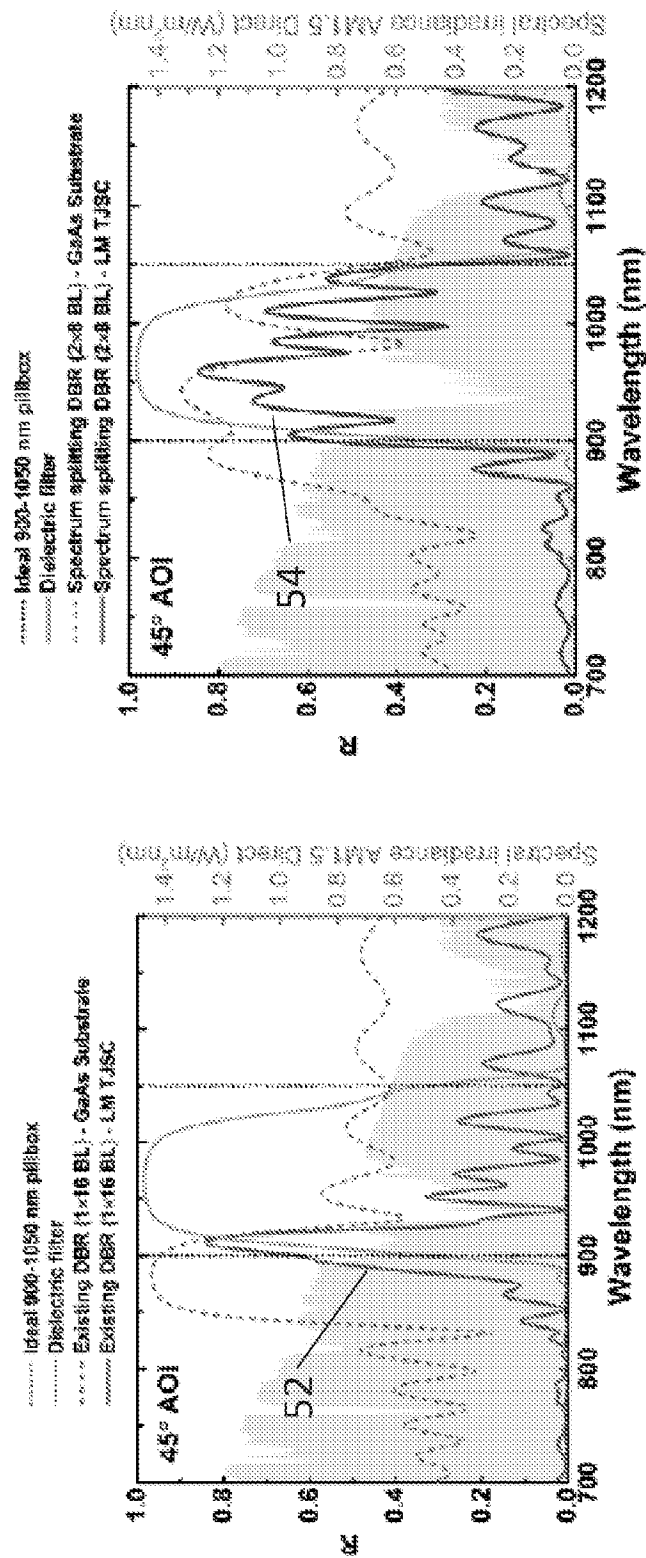


Figure 12

Figure 13

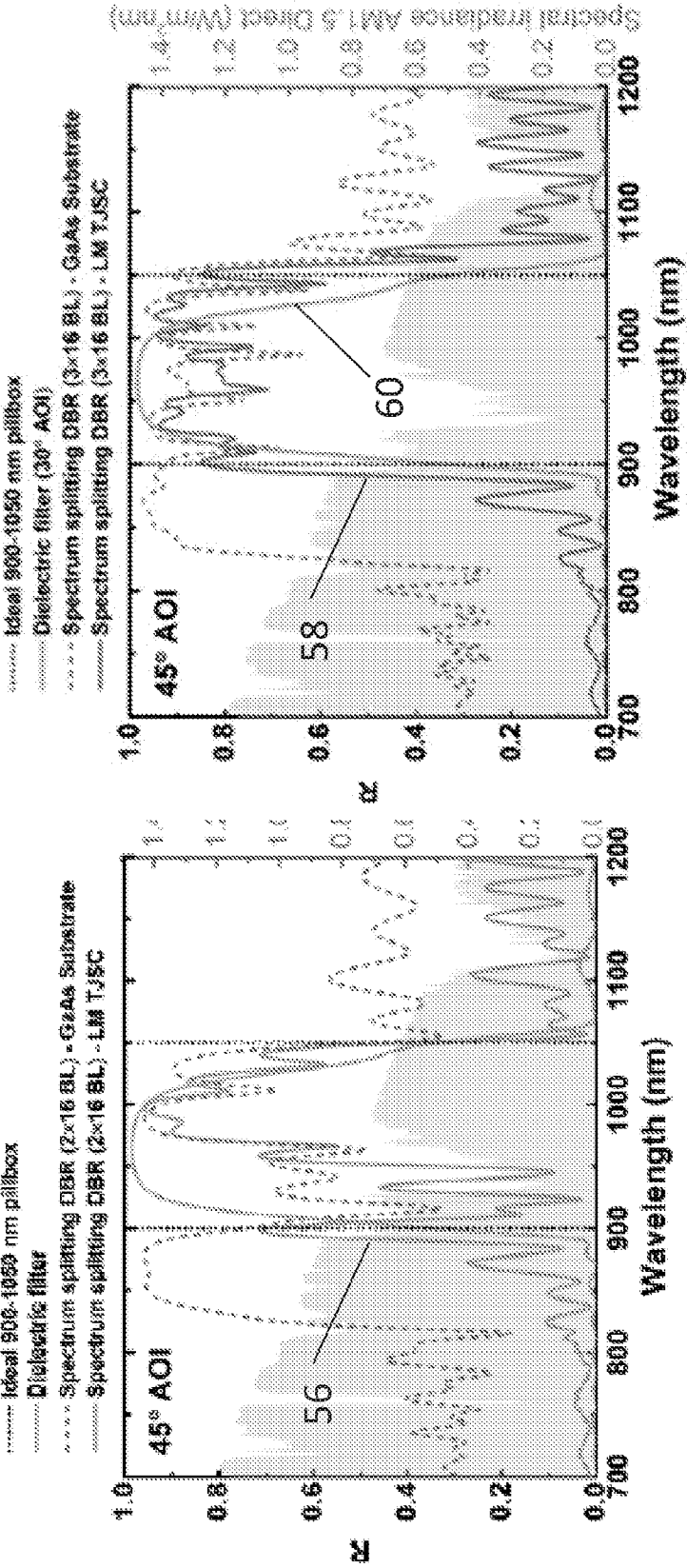


Figure 15

Figure 14

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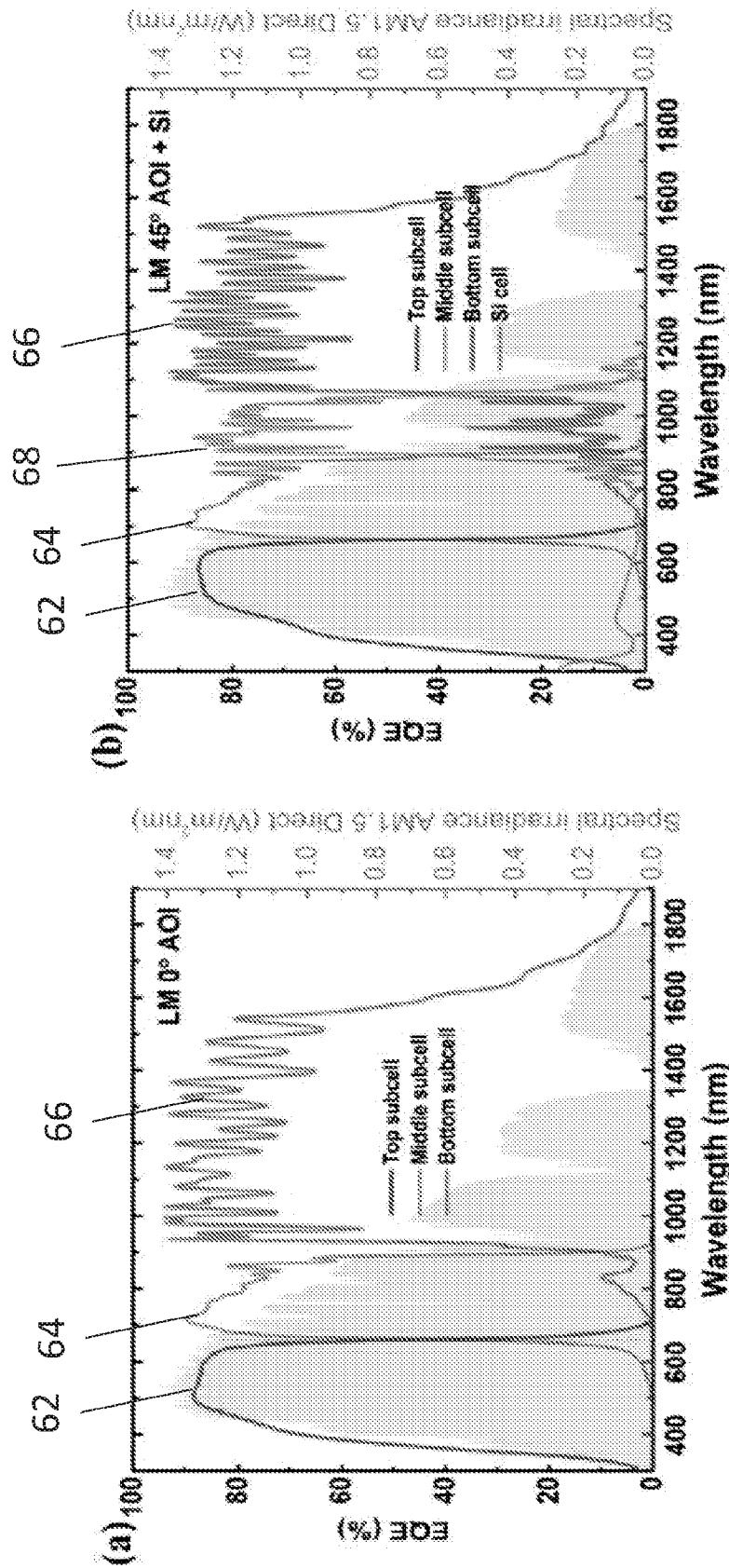


Figure 16

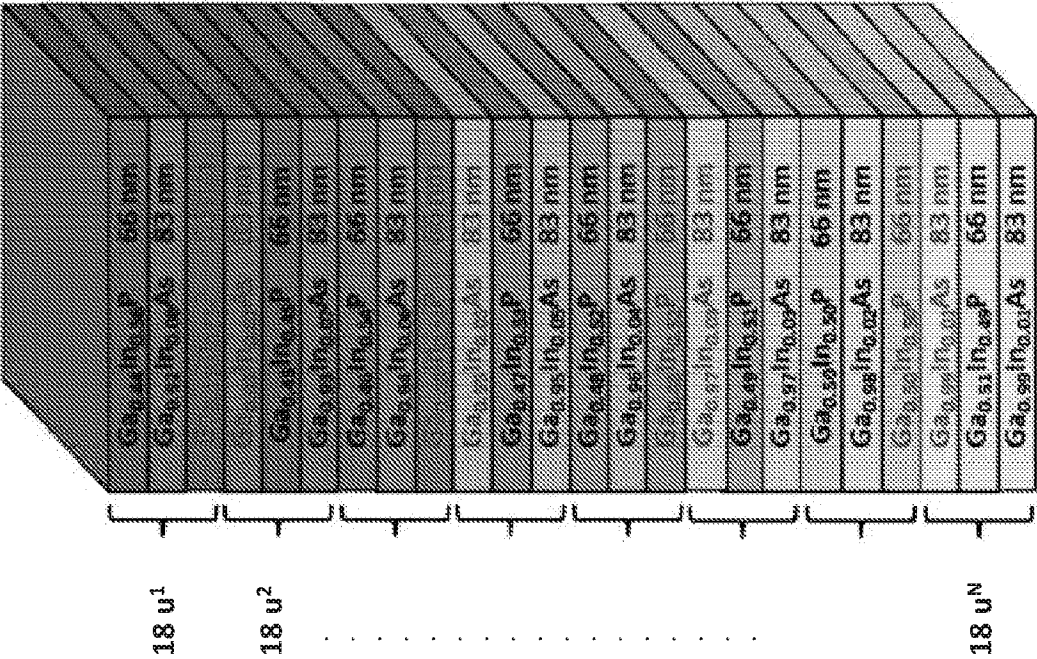


Figure 17

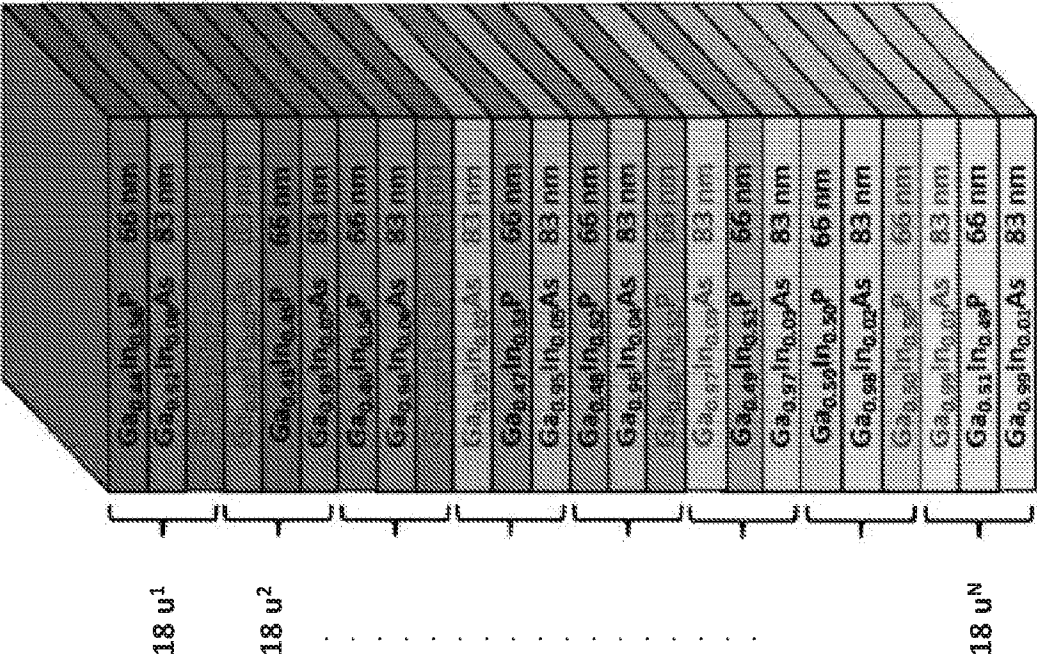


Figure 18

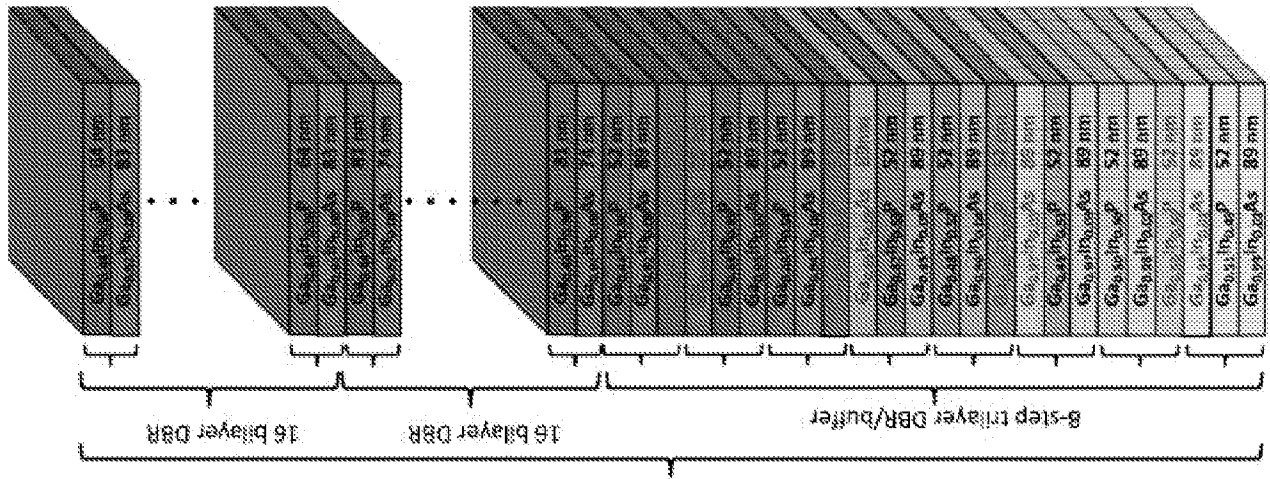
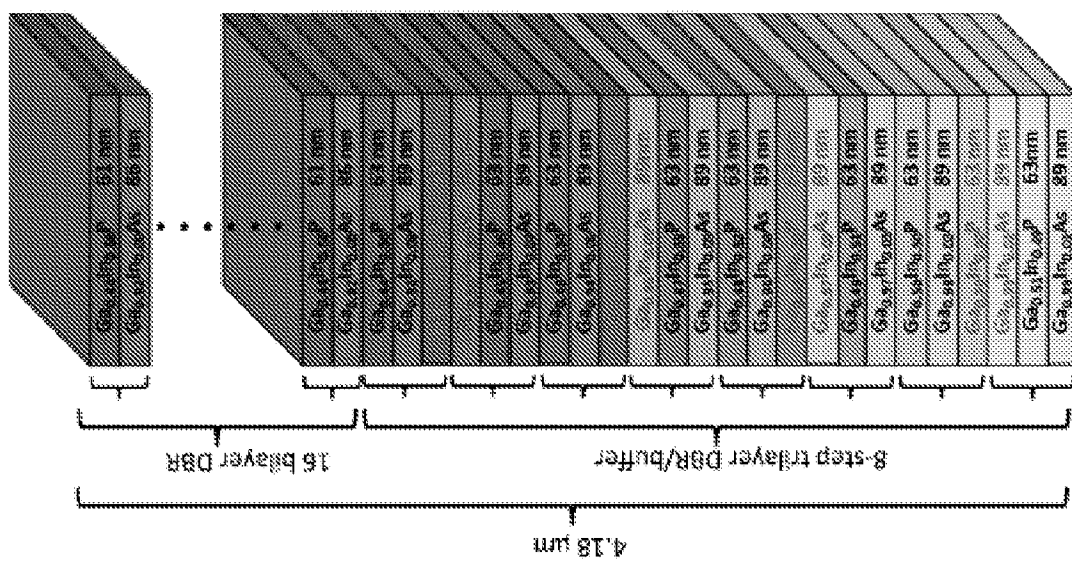


Figure 20



61253.7

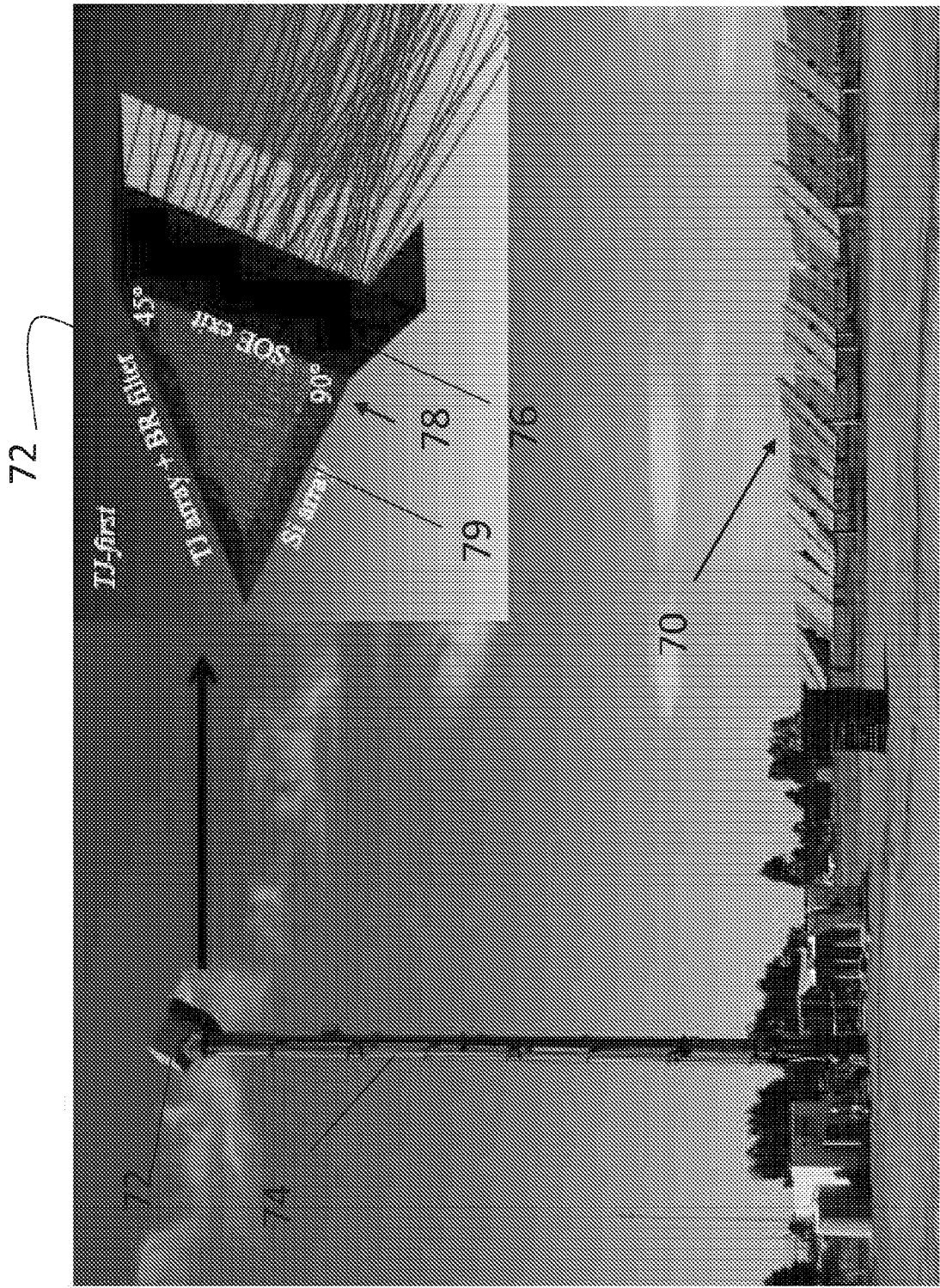


Figure 21

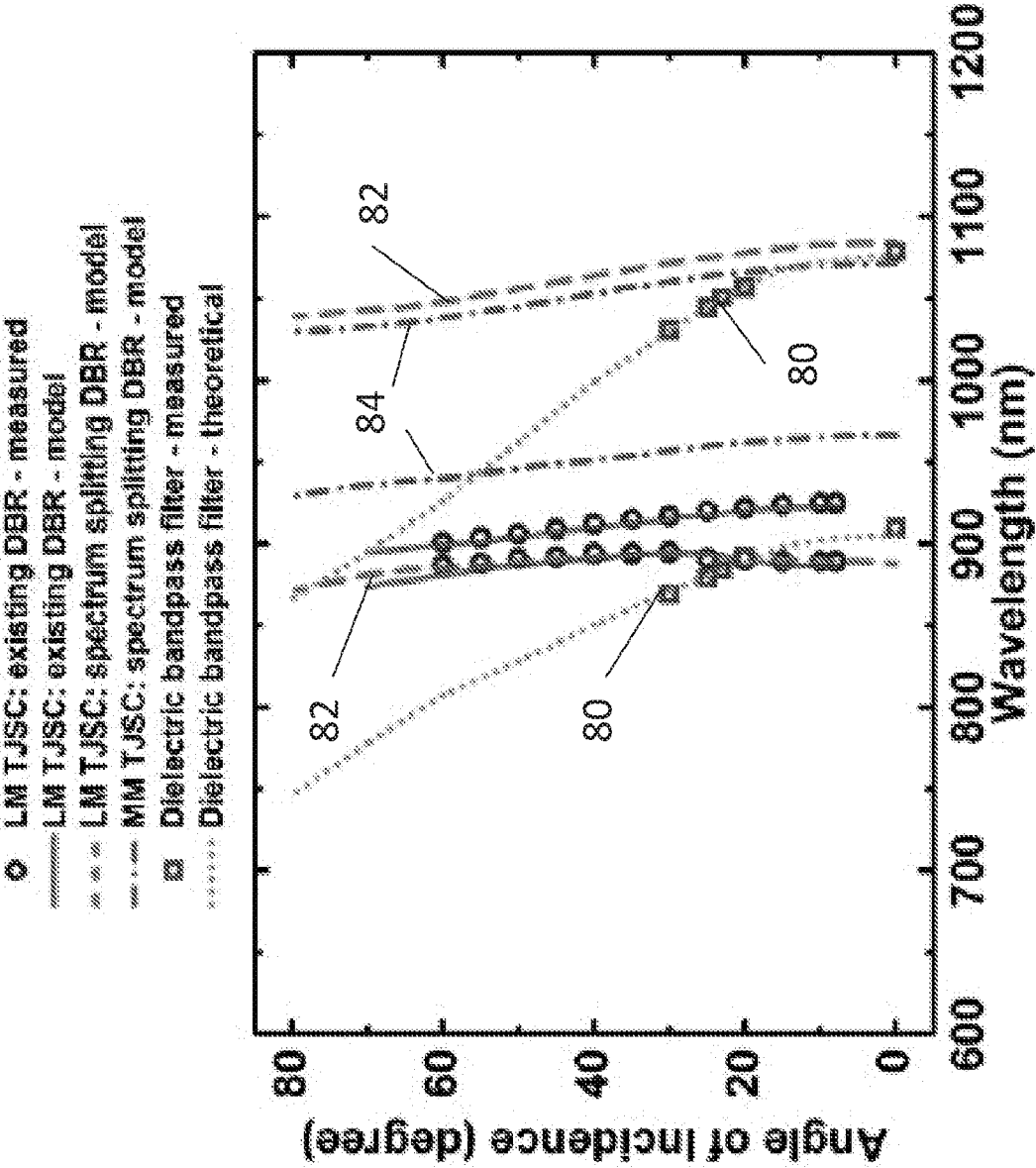


Figure 22

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2019/050611

A. CLASSIFICATION OF SUBJECT MATTER

H01L 31/047 (2014.01) H01L 31/056 (2014.01) H01L 31/0687 (2012.01) H01L 31/0735 (2012.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases: PATENW in Logical databases (WPIAP, EPODOC, Full text), IPC/CPC marks:

H01L31/047, H01L31/056, H01L31/0687, H01L51/42, and keywords: Solar, photovoltaic, PV, photoelectric, DBR, BRAGG-reflector and similar terms. Applicant(s)/Inventor(s) name search in Espacenet, AusPat and Google Patents/Google scholar/Google: Applicant name: NEWSOUTH INNOVATIONS PTY LIMITED; Inventors name: Green, Martin Andrew; Keevers, Mark; Jiang, Yajie Jessica, and keywords: solar cell, DBR, Bragg reflector, GaInP, GaInAs and similar terms. Applicant(s)/Inventor(s) name searched in internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"D" document cited by the applicant in the international application	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
1 August 2019

Date of mailing of the international search report
01 August 2019

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INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2019/050611
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/0179857 A1 (EPISTAR CORPORATION) 25 June 2015 Figs. 11A-11C, paragraphs 0044-0049	1-33
X	US 2017/0222066 A1 (SOLAERO TECHNOLOGIES CORP.) 03 August 2017 Figs. 2A-2C, paragraphs 0150-0187	1-33
X	CN 104617168 A (TIANJIN LANTIAN SOLAR TECH CO LTD) 13 May 2015 Fig. 1 and the associated text	1-33
X	Emelyanov V.M. ET AL., "Multijunction GaInP/GaInAs/Ge Solar Cells with Bragg Reflectors", Physics of Semiconductor Devices, 2010, Vol. 44, No. 12, pp. 1600-1605 Fig. 1b, 2 and the associated text	1-33
P,X	Jiang Y et al., "Design of Bragg Reflector in GaInP/GaInAs/Ge Triple-junction Solar Cells for Spectrum Splitting Applications", conference paper 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), 10-15 June 2018. whole document	1-33

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2019/050611	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2015/0179857 A1	25 June 2015	US 2015179857 A1	25 Jun 2015
		TW 201140875 A	16 Nov 2011
		TW I489652 B	21 Jun 2015
		US 2011278537 A1	17 Nov 2011
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		US 9935209 B2	03 Apr 2018
		EP 3159939 A1	26 Apr 2017
		EP 3159940 A1	26 Apr 2017
		EP 3159941 A1	26 Apr 2017
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		EP 3301727 A1	04 Apr 2018
		US 2018062017 A1	01 Mar 2018
		US 9985161 B2	29 May 2018
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		US 10256359 B2	09 Apr 2019
		US 2017110614 A1	20 Apr 2017
		US 10270000 B2	23 Apr 2019
		US 2017133542 A1	11 May 2017
		US 10361330 B2	23 Jul 2019
		US 2017110615 A1	20 Apr 2017
		US 2018166587 A1	14 Jun 2018
		US 2018190852 A1	05 Jul 2018
		US 2018269339 A1	20 Sep 2018
		US 2019088811 A1	21 Mar 2019
CN 104617168 A	13 May 2015	CN 104617168 A	13 May 2015
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2019)			