US 20140345679A1

(19) **United States**

(12) **Patent Application Publication**

Johnson

(10) **Pub. No.: US 2014/0345679 A1**

(43) **Pub. Date: Nov. 27, 2014**

(54) **MULTIJUNCTION PHOTOVOLTAIC DEVICE HAVING SIGE(SN) AND GAASNSB CELLS**

(75) Inventor: **Andrew Johnson**, Newport (GB)

(73) Assignee: **IQE PLC.**, Cardiff (GB)

(21) Appl. No.: **14/342,016**

(22) PCT Filed: **Aug. 14, 2012**

(86) PCT No.: **PCT/GB2012/051981**

§ 371 (c)(1),
(2), (4) Date: **Aug. 13, 2014**

Related U.S. Application Data

(60) Provisional application No. 61/528,650, filed on Aug. 29, 2011.

Publication Classification

(51) **Int. Cl.**

H01L 31/0725	(2006.01)
H01L 31/0216	(2006.01)
H01L 31/18	(2006.01)
H01L 31/0735	(2006.01)
H01L 31/074	(2006.01)

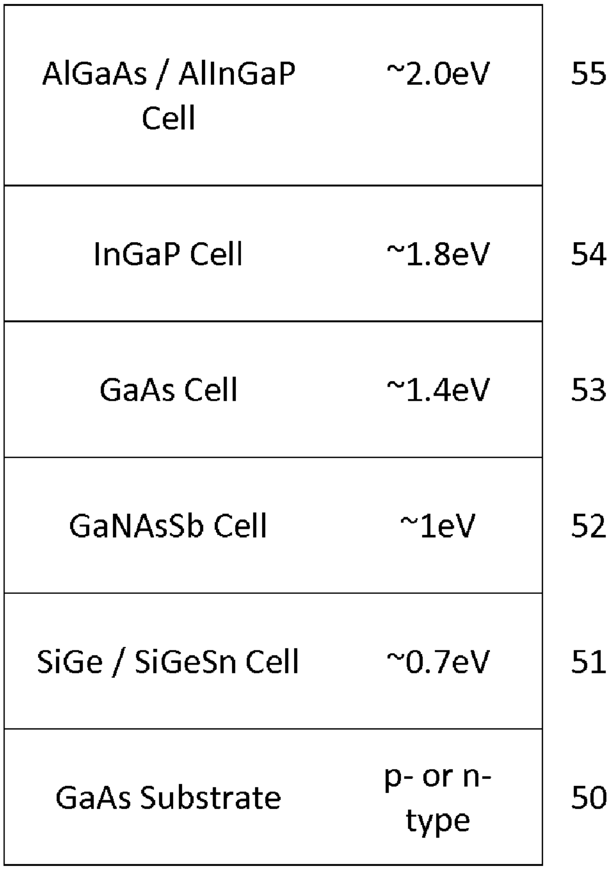
(52) **U.S. Cl.**

CPC ***H01L 31/0725*** (2013.01); ***H01L 31/0735*** (2013.01); ***H01L 31/074*** (2013.01); ***H01L 31/1812*** (2013.01); ***H01L 31/1844*** (2013.01); ***H01L 31/02167*** (2013.01)

USPC **136/255**; 438/94

(57) **ABSTRACT**

A multijunction tandem photovoltaic device is disclosed having a bottom subcell of silicon germanium or silicon germanium tin material and above that a subcell of gallium nitride arsenide antimonide material. The materials are lattice matched to gallium arsenide, which preferably forms the substrate. Preferably, further lattice matched subcells of gallium arsenide, indium gallium phosphide and aluminium gallium arsenide or aluminium indium gallium phosphide are provided.



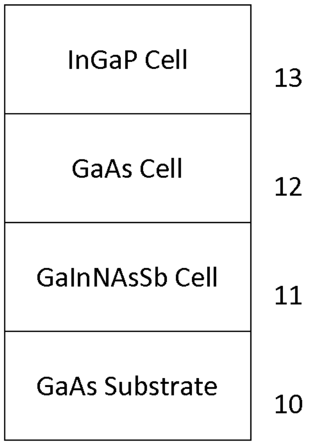


Fig. 1

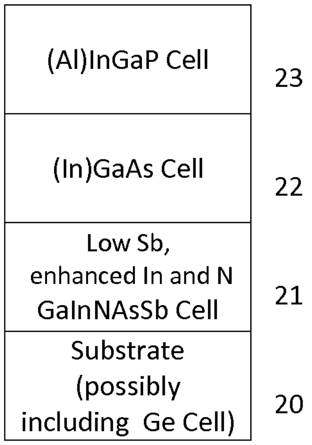


Fig.2

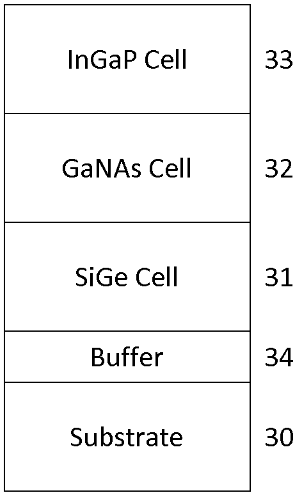


Fig. 3

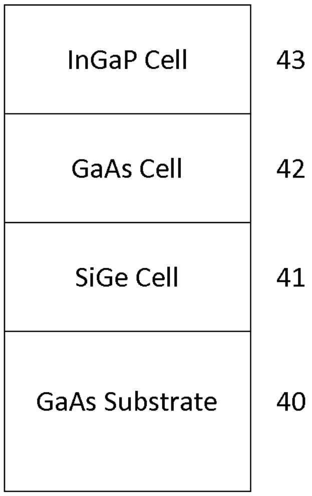


Fig. 4

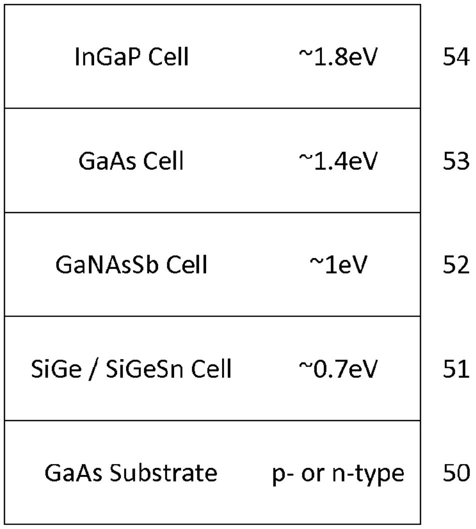

InGaP Cell
~1.8eV
54
GaAs Cell
~1.4eV
53
GaNAsSb Cell
~1eV
52
SiGe / SiGeSn Cell
~0.7eV
51
GaAs Substrate
p- or n-type
50

Fig. 5

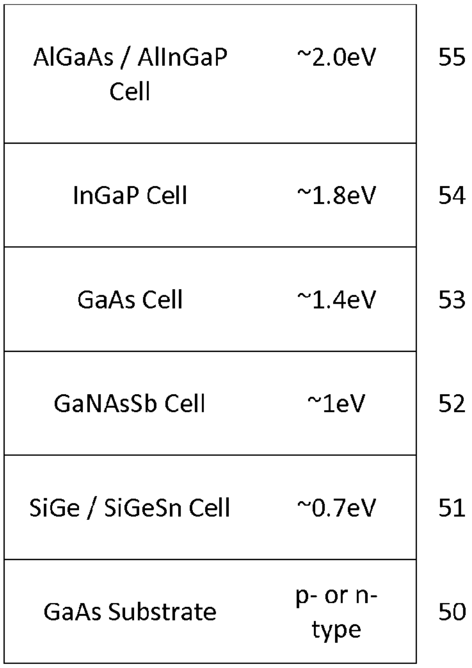

AlGaAs / AlInGaP Cell
~2.0eV
55
InGaP Cell
~1.8eV
54
GaAs Cell
~1.4eV
53
GaNAsSb Cell
~1eV
52
SiGe / SiGeSn Cell
~0.7eV
51
GaAs Substrate
p- or n-type
50

Fig. 6

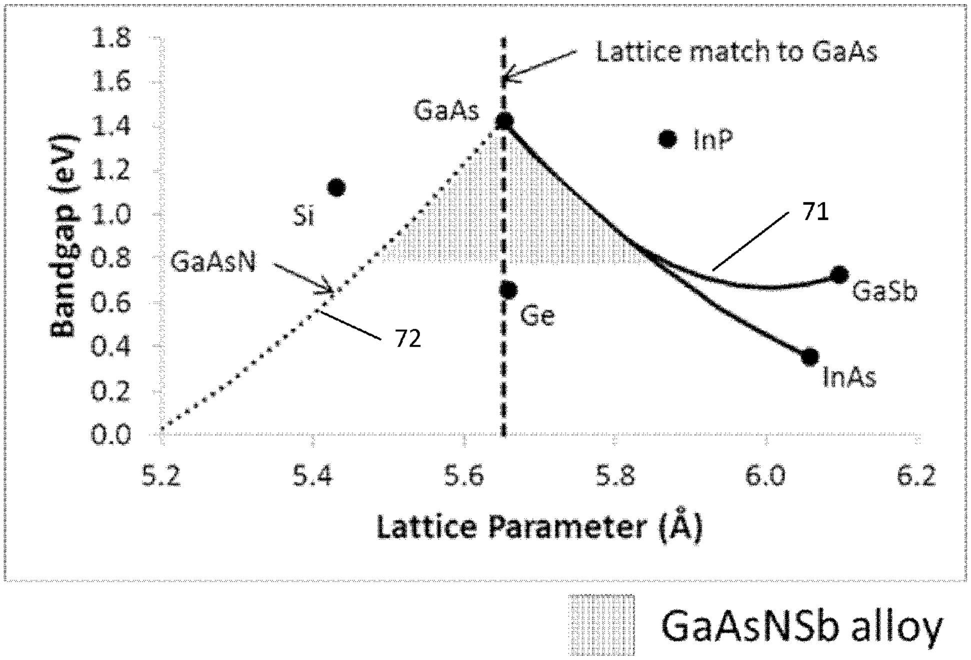

Lattice match to GaAs
GaAs
InP
Si
GaAsN
71
72
Ge
GaSb
InAs
Bandgap (eV)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
5.2
5.4
5.6
5.8
6.0
6.2
Lattice Parameter (Å)
GaAsNSb alloy

Fig. 7

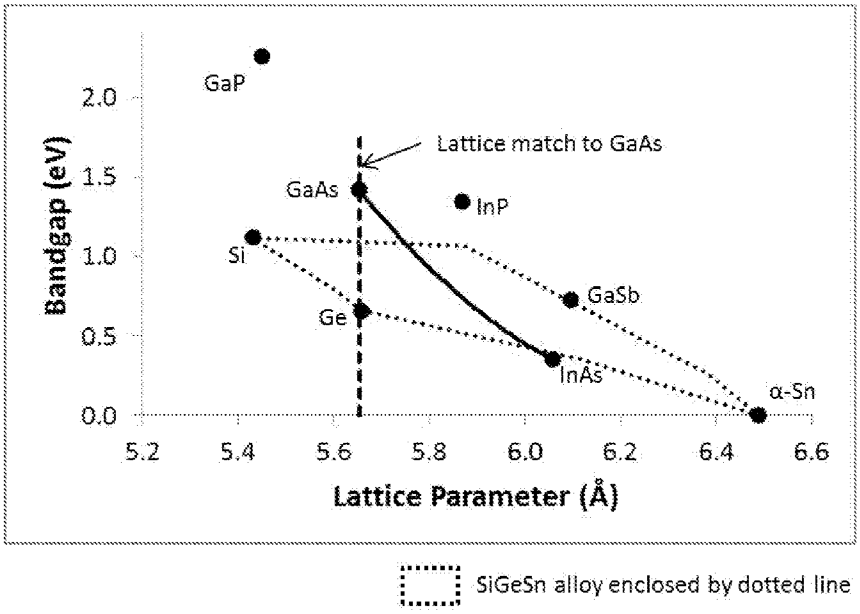

GaP
Lattice match to GaAs
GaAs
InP
Si
GaSb
Ge
InAs
α-Sn
Bandgap (eV)
2.0
1.5
1.0
0.5
0.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6
Lattice Parameter (Å)
SiGeSn alloy enclosed by dotted line

Fig. 8

MULTIJUNCTION PHOTOVOLTAIC DEVICE HAVING SIGE(SN) AND GAASNSB CELLS

[0001] The present invention relates to photovoltaic devices having more than one subcell for absorbing different parts of the spectrum of the incident light.

BACKGROUND

[0002] Multijunction photovoltaic devices comprise a series of subcells each having a light absorbing semiconductor material and a p-n junction therein to separate the photocarriers, to produce the photocurrent. They work by having a top subcell, i.e. that first exposed to the incident light, that has a large bandgap and so absorbs the shorter wavelengths in the incident light only and passes the longer wavelengths, with the next subcell having a smaller bandgap so that it can absorb part of the light passed by the subcell above, and so on. Solar cells are, of course, one kind of photovoltaic device and are ones used to convert sunlight into electricity for the purpose of generating power.

[0003] In this document "top" and "bottom" are to be understood in that sense, i.e. the top subcell is that which receives the incident light first in normal use, rather than the actual spatial orientation of the device. "Above" and "below" are also to be understood similarly, unless the context demands otherwise. Further light is not to be understood as visible light only. For example 1.0 eV and 0.7 eV bandgaps discussed in this document absorb light in the infra-red region.

[0004] Multijunction photovoltaic devices often use lattice matched material, which is to say that when one material is grown on another the lattice parameters of the two materials match to an extent that the crystal structure of the material being grown is maintained and strain relieving dislocations are not introduced. When the lattice parameters of the two materials, in the bulk form, are not quite equal the layer being grown becomes strained, i.e. its lattice parameter changes to match that of the layer on which it grown. Where the strain is quite small the layer being grown can be grown to an arbitrary thickness without the introduction of dislocations. The thickness at which strain relieving dislocations first appear is defined as the critical thickness for a material. In this context, the term lattice matched would also refer to strained layers grown to thicknesses below the critical thickness. Some examples of known multijunction solar cells are as follows.

[0005] US2009/00140161 (Harris) describes a triple junction solar cell as shown in FIG. **1** of the present application. The structure is an InGaP top subcell, a GaAs middle subcell and a GaInNAsSb bottom subcell, all lattice matched to a GaAs substrate. The aim stated by this document is to improve on the efficiency of a record holding InGaP/InGaAs/Ge solar subcell. For the GaInNAsSb material, it discloses, a bandgap of 0.9 to 1.3 eV and that it can be lattice matched to GaAs, which has a bandgap of 1.42 eV, so a GaInNAsSb subcell can be used to absorb the longer wavelengths passed by the GaAs subcell above it. The proposed proportions of In, N and Sb are respectively 0.05 to 0.07, 0.01 to 0.02 and 0.02 to 0.06. The document discloses experimental results comparing GaInNAsSb junctions to GaInNAs ones with the former achieving a better internal quantum efficiency and so it claims "The GaInNAsSb material system on substrate [GaAs] (FIG. **1**A) represents one of the smallest bandgaps ever achieved (0.92 eV) in a dilute nitride solar subcell with high carrier collection efficiency." Further it notes a merit of a 0.92 eV bandgap which is that since there is little energy in the solar spectrum between 0.85 eV and 0.92 eV due to atmospheric absorption, subcells with just smaller bandgaps than that will not provide extra photocurrent. Later it concludes, "Since GaInNAsSb-containing devices produce sufficient current this shows that using this material, rather than Ge, as the bottom junction in a triple-junction GaInP/GaAs/GaInNAsSb device has the potential to increase the power conversion efficiency of triple junction subcells according to the invention by increasing the open-circuit voltage of the devices."

[0006] US2011/0232730 (Jones) proposes a lattice matched triple junction solar cell having a similar set of subcells to that of Harris. FIG. **2** of the present application shows this structure. Again, the proposed bottom subcell **21** is GaInNAsSb, but the material is described as "low Sb, enhanced In and N". More specifically the proposed proportions of In, N and Sb are respectively 0.07 to 0.18, 0.025 to 0.04 (higher than Harris) and 0.001 to 0.03 (generally lower than Harris). The subcells are lattice matched to the substrate. Possibilities of an Al component in the top subcell **23** and of an In component in the middle subcell **22**, marked in FIG. **2**, are disclosed. These enable the materials to be lattice matched to Ge, when that is the substrate. This document also proposes that when the substrate is Ge there may be a fourth subcell in that substrate.

[0007] US2011/0083729 (Lee) also discloses a triple junction solar cell. The structure of Lee is shown in FIG. **3** of the present application. Again the top subcell **33** is InGaP, but the middle subcell **32** is GaNAs and the bottom subcell **31** is SiGe. The document notes a problem with Ge bottom subcells, which is that because of the small bandgap the current produced by Ge subcells is high compared to GaAs and InGaP top and middle subcells leading to inefficiency. The SiGe actually used has a higher bandgap and produces a current that matches that of the InGaP and GaNAs top and middle subcells proposed. In this device the lattice matching is limited. In one example, the top, middle and bottom subcells are lattice matched to each other at 5.641 Å with the subcells having the following compositions $Ga_{0.544}In_{0.456}P$, $GaN_{0.0092}As_{0.9908}$, and $Si_{0.04}Ge_{0.96}$. However these subcells are not lattice matched to the substrate **30**, which may be of various materials, and a metamorphic buffer layer **34** is employed to reduce the strain. This is produced by changing the composition of the buffer layer while it is grown to change the lattice parameter, which is not only a complex operation but will introduce defects into the structure.

[0008] GB2467934, also owned by the present applicant company, discloses a multijunction solar subcell, shown in FIG. **4** of the present application, which has a InGaP top subcell **43**, a GaAs middle subcell **2** and a SiGe subcell **41**, all lattice matched to a GaAs substrate **40**.

[0009] WO2009/157870 (Yoon) discloses an advantageous method for fabricating GaNAsSb, which method, as is explained below, may be used in the preferred examples of the invention. The disclosure of this document is incorporated herein by reference.

SUMMARY OF INVENTION

[0010] According to the present invention there is provided a multijunction photovoltaic device comprising:

- **[0011]** a set of semiconductor material layers, the layers including:
- **[0012]** a first light absorbing layer of silicon germanium or silicon germanium tin material including a photocarrier separating p-n junction,

[0013] a second light absorbing layer of gallium nitride arsenide antimonide material including a photocarrier separating p-n junction,

[0014] wherein the silicon germanium or silicon germanium tin layer and the gallium nitride arsenide antimonide layer are lattice matched to gallium arsenide.

[0015] The multijunction photovoltaic device may further comprise a light absorbing layer of gallium arsenide material including a photocarrier separating p-n junction.

[0016] The multijunction photovoltaic device may further comprise a light absorbing layer of indium gallium phosphide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

[0017] The multijunction photovoltaic device may further comprise a light absorbing layer of aluminium gallium arsenide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

[0018] The multijunction photovoltaic device may further comprise a light absorbing layer of aluminium indium gallium phosphide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

[0019] These additional layers absorb shorter wavelengths than the silicon germanium, or silicon germanium tin, and gallium nitride arsenide antimonide layers.

[0020] The multijunction photovoltaic device may comprise a gallium arsenide substrate, the set of layers being on and lattice matched to the substrate. Alternatively the multijunction photovoltaic may comprise a substrate that is lattice matched to gallium arsenide, the set of layers being on and lattice matched to the substrate.

[0021] The multijunction photovoltaic device may be a solar cell.

[0022] The present invention also provides a method of making a multijunction photovoltaic device comprising:

[0023] providing a substrate of gallium arsenide or another material that is lattice matched to gallium arsenide,

[0024] growing a first light absorbing layer of silicon germanium or silicon germanium tin material, including a photocarrier separating p-n junction, lattice matched to the substrate,

[0025] growing a second light absorbing layer of gallium nitride arsenide antimonide material, including a photocarrier separating p-n junction, lattice matched to the first light absorbing layer.

[0026] The method may comprise growing a light absorbing layer of gallium arsenide material, including a photocarrier separating p-n junction.

[0027] The method may comprise growing a light absorbing layer of indium gallium phosphide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

[0028] The method may comprise growing a light absorbing layer of aluminium gallium arsenide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

[0029] The method may comprise growing a light absorbing layer of aluminium indium gallium phosphide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

[0030] The method may comprise providing at least one further layer between two neighbouring ones of the said light absorbing layers, the at least one further layer being lattice matched to gallium arsenide.

[0031] The method may comprise removing the substrate.

[0032] Preferably the light absorbing layers are arranged in order of bandgap. This may often mean that they are grown in order of bandgap but it would be possible to grow only some of the light absorbing layers, remove the substrate and continue growth in the other direction (a substrate usually being provided on the other side).

[0033] The light absorbing layers with their p-n junctions of the invention may, as is known in the art, each be comprised in a respective region of a multijunction photovoltaic device conventionally known as a subcell, which may have further layers.

[0034] The gallium nitride arsenide antimonide subcell and silicon germanium, or silicon germanium tin, subcell of the invention are able between them to provide good absorption coverage of the spectral wavelengths longer than those absorbed by, for example, a gallium arsenide subcell, offering high absorption efficiency. This is in contrast of the approach of US2009/00140161 (FIG. **1**) and US2011/0232730 (FIG. **2**) which have only one such subcell, and in those the subcell is of a different and more complex material, namely GaInNAsSb. Further, the former document explicitly states that the goal is to have as small a bandgap as possible for the GaInNAsSb. Also, in US2011/0083729 (FIG. **3**) there are GaNAs and SiGe layers that absorb in this general area of the spectrum but GaNAs cannot be lattice matched to GaAs which means that in that device a strain relieving buffer layer has to be used between its subcells and the substrate. Further this device has no subcell in the 1.4 eV region that would be provided by GaAs, and none could be provided simply because it would not lattice match the GaNAs—further, the InGaP subcell in this device would in order to lattice match GaNAs have a larger bandgap (by changing the proportion of In and Ga) than the InGaP subcell used in the examples of the present invention which is lattice matched to GaAs, leaving a large gap in the absorption spectrum of the device of US2011/0083729.

[0035] As noted above, subcells, both in the invention and as is known generally in the art, may comprise additional layers. For example, as is known in the art, tunnel contacts may be inserted between the light absorbing subcells of multijunction photovoltaic devices, and these may be so used in the present invention, to provide good electrical connection between the subcells, and to allow the p-n junction in the neighbouring subcells to have the same polarity so that current may flow through the device. Window layers and back surface field (BSF) layers, as also known in the art, are preferably also incorporated into the structure of the device of the invention. A window is usually provided at the top of each cell and a back surface field at the bottom of each subcell and these are preferably provided in the invention. However, as noted later the invention does provide an advantage in relation to these.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] Examples of the invention will now be described, with reference to the accompanying drawings of which:

[0037] FIG. **1** shows the subcells of a first known multijunction solar cell,

[0038] FIG. **2** shows the subcells of a second known multijunction solar cell,

[0039] FIG. **3** shows the subcells of a third known multijunction solar cell,

[0040] FIG. **4** shows the subcells of a fourth known multijunction solar cell,

[0041] FIG. **5** shows the subcells of a first example of a multijunction photovoltaic device in accordance with the invention,

[0042] FIG. **6** shows the subcells of a second example of a multijunction photovoltaic device in accordance with the invention,

[0043] FIG. **7** is a graph showing the bandgap of GaAs and GaNAs of various compositions and the possibilities of bandgap of GaNAsSb when lattice matched to GaAs, and

[0044] FIG. **8** is a graph showing the bandgap and lattice parameter of the alloy SiGeSn, showing that it can be lattice matched to GaAs with a bandgap range of 0.66-~1.1 eV.

EXAMPLES

[0045] FIG. **5** shows the subcells of first example of a multijunction photovoltaic device, in particular a solar cell, in accordance with the invention. This comprises a series of subcells to absorb incident light, formed on a GaAs substrate **50**. The light is first incident on the subcell **54**, which in this example is furthest from the substrate, with light not absorbed by each subcell passing to the next. In this example there are a top subcell **54** comprising a light absorbing layer of InGaP material, an upper middle subcell **53** comprising a light absorbing layer of GaAs **52** and a lower middle subcell comprising a light absorbing layer of GaNAsSb material and a bottom subcell **51** comprising a light absorbing layer of SiGe material, all of which are lattice matched to a GaAs substrate **50**. The light absorbing material layer of each of these subcells contains a p-n junction to separate the photocarriers generated. Preferably the cells are connected in series (tandem cell).

[0046] In this example, additional layers, which are tunnel contacts (which are provided between the subcells to provide good electrical contact), windows and back surface fields, are incorporated into the structure. These are between the subcells and above and below the light absorbing layers as appropriate. These additional layers are also lattice matched to the GaAs substrate, but as their use is well known in the art and for simplicity of illustration these layers not shown in FIG. **5** (similarly for FIG. **6**). Because all the layers are lattice matched, including to the substrate, this reduces the cost of manufacture and enhances device performance, reliability and yield. Another advantage of this example is the ability, compared to devices having a Ge substrate with a light absorbing subcell in that, to put a back surface field (BSF) below the p-n junction of SiGe bottom sub-cell for enhanced device performance. Additionally, a sacrificial release layer that has a differential etch rate to GaAs may be grown below the SiGe subcell. This permits the epitaxial layer structure containing the subcells to be removed from the GaAs substrate and transferred to a suitable handle or heat sink, allowing the GaAs substrate to be re-used and if needed reducing the weight of the device. These additional layers are grown epitaxially on the GaAs substrate before the SiGe subcell is grown. Alternatively the subcells may be grown in reverse order on a GaAs substrate (or a substrate lattice matched to GaAs) starting with the widest bandgap subcell (the InGaP subcell in the case of FIG. **5**) and then followed by the narrower bandgap subcells in order (the GaAs subcell, then the GaNAsSb subcell and then the SiGe/SiGeSn subcell in the case of FIG. **5**). A sacrificial layer is provided between the widest bandgap subcell and the GaAs substrate allowing the subcells to be removed and transferred to a suitable handle or heat sink, inverted so that the narrowest bandgap cell is next to the handle or heart sink and the widest bandgap cell receives the incident light first.

[0047] The composition of the light absorbing GaNAsSb layer of subcell **52** is such that its bandgap is preferably in the range $0.8<E_g<1.2$ eV. A bandgap of around 1.0 eV is particularly advantageous since it fills the gap between the parts of the spectrum absorbed by the SiGe and GaAs layers.

[0048] FIG. **7** is a graph showing the bandgap of various Group III-V semiconductor materials and Group IV materials versus their lattice parameter. There are of course numerous III-V materials but the ones shown are selected either to illustrate the GaNAsSb material used in the light absorbing layer of subcell **52** of the invention or for general comparison with well-known materials. In particular a solid line **71** extends between the points for GaAs and GaSb giving the values for the ternary compound $GaAs_{1-y}Sb_y$ as the proportion y of Sb atoms varies. Dotted line **72** extending from the point for GaAs towards that for GaN, which is off the graph shown at a smaller lattice parameter, giving the values for the ternary compound $GaAs_{1-x}N_x$ as the proportion x of N atoms varies. This Figure shows that the substitution of a proportion the As atoms in GaAs by either N or Sb to GaAs reduces the bandgap (even to the range of that of Ge—while it is not practical to add more than a few percent of N that is sufficient to reach the bandgap of Ge). However substituting in N reduces the lattice parameter, while substituting in Sb increases the lattice parameter. It turns out that substituting in both N and Sb for As, i.e. to form the quaternary material $GaN_xAs_{1-x-y}Sb_y$, still causes the bandgap to decrease from that of GaAs and with certain proportions of N and Sb the material is lattice matched to GaAs (the effects on lattice parameter of N and Sb cancelling each other out). An exact lattice match to GaAs is shown by the vertical dashed line, but strained materials having layer thicknesses below the critical thickness are also possible and lie to either side of the dashed line. The shaded area shows possibilities for the quaternary GaNAsSb having bandgaps of the most interest in the invention. Note, in particular, that the region neighbouring the dashed vertical line (which is the lattice matched region) that is within the shaded area also does include bandgaps in the region of 1 eV between that of SiGe (around 0.7 eV) and GaAs (around 1.4 eV).

[0049] The precise proportions of N and Sb in the GaNAsSb for a particular bandgap and lattice matching can of course be experimentally determined easily for any particular case. However for lattice matching to GaAs the ratio of N to Sb is about 1:2.6. For bandgaps equal to GaAs (1.4 eV) down to 0.9 eV the respective proportion of N and Sb, x and y, in the material lie in the range $0<x<6\%$ and $0<y<16\%$.

[0050] To make the SiGe light absorbing layer in subcell **51** lattice matched to GaAs the proportion of silicon is around 0.018 and this material then has a bandgap of around 0.7 eV. As can be seen in FIG. **8**, which is another graph showing the bandgap of various Group III-V semiconductor materials and Group IV materials versus their lattice parameter, Ge is not lattice matched to GaAs but as the difference is not large only a small amount of Si needs to be added to achieve the lattice matching. Since SiGe is a binary compound there is only one degree of freedom provided by the proportion of the atoms and so the bandgap is fixed at around 0.7 eV if the lattice match to GaAs is to be maintained.

[0051] However, if desired a larger bandgap can be obtained for subcell **51** by using SiGeSn instead of SiGe. This material is lattice matched to GaAs where the ratio of Si to Sn is approximately 4:1. Where for example the proportion of Si is 2% and that of Sn is 0.5% this provides a larger bandgap than SiGe lattice matched to GaAs, where the proportion of Si is 8% and that of Sn is 2% the bandgap is wider, and where the proportions are much larger the bandgap can extend further.

[0052] FIG. **6** shows the subcells of a second example of the invention. This device is as that of FIG. **5** but it has an additional subcell **55** having a light absorbing layer and a photocarrier separating p-n junction located above the InGaP subcell **54**. This subcell **55** absorbs part of the spectrum above around 2.0 eV and allows longer wavelengths to be absorbed by the InGaP subcell **54** and the subcells below that. The material of the light absorbing layer of this subcell **55** in this example is AlGaAs having a proportion of Al and Ga having the desired bandgap. This material is lattice matched to GaAs, although strained, at all proportions of Al to Ga, and can be grown to thicknesses required for a photovoltaic device to have sufficient absorption without any strain relaxation.

[0053] In another similar example the light absorbing material layer of subcell **55** is AlInGaP lattice matched to GaAs. Again the bandgap of is preferably about 2.0 eV but since the material is a quaternary some extra flexibility is obtained.

[0054] The subcells examples of FIGS. **5** and **6** described above do not, as is preferred, have further subcells between them. That is however possible with preferably the bandgaps of the light absorbing materials of the intervening subcells being between that of their neighbours.

[0055] Note also that while the substrate of the examples is GaAs the invention also extends to cases where the substrate on which the subcells are grown is another material that is lattice matched to GaAs.

[0056] Note further that if not needed for certain applications any one or more of subcells **53**, **54** or **55** can be omitted.

[0057] The materials of the subcells may be grown using epitaxial techniques including MBE and MOCVD.

[0058] For example, GB2467934, also owned by the present applicant company and mentioned above, discloses examples of SiGe materials manufactured on GaAs substrates. The document is incorporated herein by reference. These materials can be grown using an epitaxy process, using a germanium containing precursor (e.g GeH_4, $GeCl_4$, etc.) and a silicon containing precursor (e.g. SiH_4, SiH_2Cl_2, $SiHCl_3$, disilane etc.) with a carrier gas (e.g. H_2). The p-n junction used to separate the photo carriers may be formed in the SiGe material by various methods. These include doping during the epitaxial growth, or by diffusion in of dopant into a layer of the material when it is grown or is partially grown. An alternative method is given below.

[0059] The SiGe or SiGeSn material used in subcell **51** will in many examples have III-V material directly grown on it. There may then be diffusion of Group V atoms from the III-V material into the SiGe or SiGeSn. Arsenic atoms, for example, will do this. Arsenic in SiGe or SiGeSn is an n-type dopant.

[0060] So if the SiGe or SiGeSn neighbouring the III-V material grown on it is p-type then the Group V atoms diffusing into the SiGe or SiGeSn may well dope the SiGe or SiGeSn forming a p-n junction below the surface of the SiGe or SiGeSn. (If this junction were to be parasitic in a particular example it can be prevented or controlled by forming a thin Si diffusion barrier between the SiGe or SiGeSn. Three atomic layers is sufficient.) However, as foreshadowed, the junction so formed can be utilised as the photocarrier separating junction in the SiGe or SiGeSn subcell. Alternatively it may be used as a tunnel diode between the SiGe or SiGeSn subcell and the subcell grown on that. A thinner Si barrier can be used to control the amount of diffusion if that is desired.

[0061] On the other hand if the SiGe or SiGeSn neighbouring III-V material grown on it is n-type (i.e. an epitaxially grown SiGe or SiGeSn p-n junction) the diffusion in of Group V atoms will not form an extra p-n junction.

[0062] The GaNAsSb of the invention layer is also formed by epitaxy. The p-n junction for separating the photocarriers therein is formed either by doping during the epitaxial growth, or, alternatively, after the layer, or part thereof has been grown and diffusing the dopant in. The above mentioned WO2009/157870 described a particularly advantageous method for growing this material.

[0063] GB2467934, and also GB2467935 also owned by the present applicant, describe techniques that may be employed in the present invention to remove the GaAs substrate from the rest of the device. Those documents are therefore incorporated by reference. This is useful, for example, to reduce weight of the device (useful for space applications), to allow a heat sink to be bonded to the device or to allow the substrate to be re-used to reduce cost.

[0064] The GaAs substrate may be removed when all the subcells have been grown in order on it (which may be in either order). Alternatively the GaAs substrate can be removed at any point during the growth and that may be part way through a subcell including partway through the just one cell. In these methods a new substrate is mounted on the just grown surface.

1. A multijunction photovoltaic device comprising: a set of semiconductor material layers, the layers including:

a first light absorbing layer of silicon germanium or silicon germanium tin material including a photocarrier separating p-n junction,

a second light absorbing layer of gallium nitride arsenide antimonide material including a photocarrier separating p-n junction,

wherein the silicon germanium or silicon germanium tin layer and the gallium nitride arsenide antimonide layer are lattice matched to gallium arsenide.

2. A multijunction photovoltaic device as claimed in a claim **1** further comprising a light absorbing layer of gallium arsenide material including a photocarrier separating p-n junction.

3. A multijunction photovoltaic device as claimed in claim **1** further comprising a light absorbing layer of indium gallium phosphide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

4. A multijunction photovoltaic device as claimed in claim **1** further comprising a light absorbing layer of aluminium gallium arsenide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

5. A multijunction photovoltaic device as claimed in claim **1** further comprising a light absorbing layer of aluminium indium gallium phosphide including a photocarrier separating p-n junction and being lattice matched to gallium arsenide.

6. A multijunction photovoltaic device as claimed in claim **1** comprising a gallium arsenide substrate, the set of layers being on and lattice matched to the substrate.

7. A multijunction photovoltaic device as claimed in claim **1** comprising a substrate that is lattice matched to gallium arsenide, the set of layers being on and lattice matched to the substrate.

8. A multijunction photovoltaic device as claimed in claim **1** wherein the photovoltaic device is a solar cell.

9. A method of making a multijunction photovoltaic device comprising:

providing a substrate of gallium arsenide or another material that is lattice matched to gallium arsenide,

growing a first light absorbing layer of silicon germanium or silicon germanium tin material, including a photocarrier separating p-n junction, lattice matched to the substrate,

growing a second light absorbing layer of gallium nitride arsenide antimonide material, including a photocarrier separating p-n junction, lattice matched to the first light absorbing layer.

10. A method as claimed in claim **9** comprising growing a light absorbing layer of gallium arsenide material, including a photocarrier separating p-n junction.

11. A method as claimed in claim **9** comprising growing a light absorbing layer of indium gallium phosphide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

12. A method as claimed in claim **9** comprising growing a light absorbing layer of aluminium gallium arsenide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

13. A method as claimed in claim **9** comprising growing a light absorbing layer of aluminium indium gallium phosphide, including a photocarrier separating p-n junction, lattice matched to gallium arsenide.

14. A method as claimed in claim **9** comprising providing at least one further layer between two neighbouring ones of the said light absorbing layers, the at least one further layer being lattice matched to gallium arsenide.

15. A method as claimed in claim **9** comprising removing the substrate.

* * * * *