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[Continued on next page]

(54) **Title**: A METHOD FOR IMPROVING THE QUALITY OF A TUNNEL JUNCTION IN A SOLAR CELL STRUCTURE

(57) **Abstract**: A method of forming a tunnel junction (112) in a solar cell structure (100) alternates between depositing a Group III material and depositing a Group V material on the solar cell structure (100).

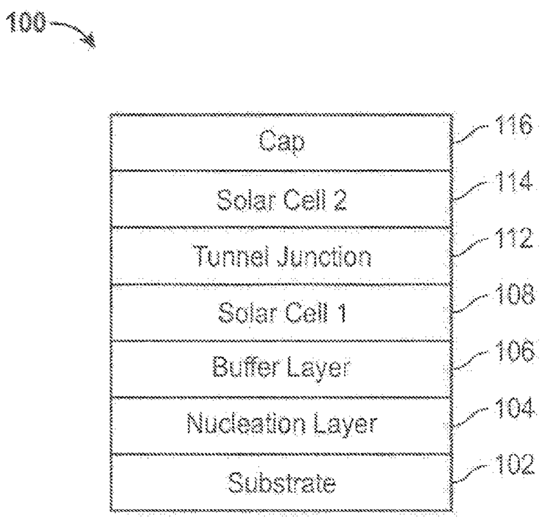

FIG. 1

WO 2012/148618 A1

Declarations under Rule 4.17:

— *as to the identity of the inventor (Rule 4.17(i))*

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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A METHOD FOR IMPROVING THE QUALITY OF A TUNNEL JUNCTION IN A SOLAR CELL STRUCTURE

Background

Embodiments of this disclosure relate generally to multiple junction solar cell structures, and more particularly, to a method for improving the quality of tunnel junctions in multiple junction solar cell structures.

Solar photovoltaic devices are devices which are able to convert solar radiation into usable electrical energy. Solar energy created through photovoltaic devices is the main source of power for many spacecraft. Solar photovoltaic devices are also becoming an attractive alternative for power generation for home, commercial, and industrial use since solar energy is environmentally friendly and renewable.

In multiple junction solar cell structures for concentrator photovoltaic application, tunnel junctions in between individual solar may play an important role in determining the efficiency of the solar cell structure. One way to increase the efficiency of the solar cells may be to improve the tunnel junction material quality and therefore the material quality of the layers grown on the tunnel junction, meanwhile to increase tunneling current from the tunnel junctions. Further, the tunnel junction needs to be transparent enough to allow light to pass through for underneath solar cells to absorb.

Therefore, it would be desirable to provide a system and method that overcomes the above problems.

SUMMARY

A method of forming a tunnel junction in a solar cell structure comprises depositing a Group III material; and depositing a Group V material after deposition of said Group III material.

A method of forming a tunnel junction in a solar cell structure comprises alternating between depositing a Group III material and depositing a Group V material on the solar cell structure.

A photovoltaic device has a substrate. A first solar cell device is positioned above the substrate. A contact is positioned above the first solar cell. A tunnel junction is formed between the first solar cell and the contact. The tunnel junction is formed by migration-enhanced epitaxial (MEE).

The features, functions, and advantages can be achieved independently in various embodiments of the disclosure or may be combined in yet other embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

Figure 1 is a simplified block diagram of a solar cell structure which may use a migration-enhanced epitaxial method to form the tunnel junction;

Figure 2 is a timing diagram of a migration-enhanced epitaxial flow sequence during formation of the tunnel junction;

Figure 3 is a flow chart showing a migration-enhanced epitaxial flow sequence during formation of the tunnel junction;

Figure 4 shows the light I-V (LIV) performance of a migration-enhanced epitaxial grown

GaInP tunnel junction at high temperature (HT) and conventional epitaxy grown GaInP tunnel junction (TuJn) at same temperature in a test structure.

DETAILED DESCRIPTION

Referring to Figure 1, a multi-solar cell structure **100** (hereinafter solar cell structure 100) is shown. The solar cell structure **100** may have a substrate **102**. The substrate **102** may be formed of different materials. In accordance with one embodiment, gallium arsenide (GaAs), germanium (Ge), or other suitable materials may be used. The list of the above material should not be seen in a limiting manner. If a germanium (Ge) substrate is used, a nucleation layer 104 may be deposited on the substrate **102**. On the substrate **102** or over the nucleation layer 104, a buffer layer 106 may then be formed. A solar cell **108**, e.g., Solar Cell 1, may be formed on the buffer layer **106.** The solar cell **108** may be formed of an n+ emitter layer and a p-type base layer. In accordance with one embodiment, Gallium (Ga) Indium (In) Phosphorus (P) may be used to form the solar cell 108. However, this should not be seen in a limiting manner.

A tunnel junction **112** may be formed between the solar cell **108** and another solar cell **114**, e.g., Solar Cell 2. The tunnel junction **112** may be used to connect the solar cell **114** and solar cell **108**. The solar cell **114** may be similar to that of solar cell **108**. The solar cell **114** may be formed of an n+ emitter layer and a p-type base layer. In accordance with one embodiment, Gallium (Ga) Indium (In) Phosphorus (P) may be used to form the solar cell **114**. However, this should not be seen in a limiting manner. A cap layer **116** may be formed on the solar cell **114**. The cap layer **116** serves as a contact for the solar cell structure **100**. While **Figure 1** shows solar cells **108** and **114**, additional solar cells and tunnel junctions may be used.

The quality of the tunnel junction **112** may be critical to keep the solar cell **114** on top of

the tunnel junction **112** in high crystal quality. By providing a high quality tunnel junction

112, a higher tunnel junction current may be generated. This may enhance the efficiency of the solar cell structure **100**.

Presently, in existing high efficiency multi-junction solar cells lower temperatures may be used to achieve high doping concentration, particularly with the high bandgap materials like GaInP. Referring now to **Figures 2** and **3**, a method which may improve the quality of the tunnel junction **112** is disclosed. The method may use a migration enhanced epitaxial (MEE) method to form the tunnel junction **112**.

MEE is a method of depositing single crystals. MEE may use group III and group V atoms alternatively, so that group III atoms have a longer diffusion length on the surface before reacting with group V atoms, and therefore achieve higher crystal quality. In forming the tunnel junction **112**, different combinations of Group III and Group V elements listed in the periodic table may be used. Different combinations may be used based on lattice constant and bandgap requirements. Group III elements may include, but is not limited to: boran (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl). Group V elements may include, but is not limited to: nitrogen (N), phosphorus (P), arsenic (As), antimony (Sb), and bismuth (Bi).

Migration of surface atoms along the surface may be very important for growing high quality layers and atomically flat heterojunctions. MEE is using group III and group V modulation during the epitaxial which may enhance the group III atoms migrating on the substrate surface and therefore increase the quality. As shown in **Figures 2** and **3**, one alternates between the application of Group III and Group V materials. Thus, Group III material may first be applied to the TuJn layer **112**. This may allow the Group III material a longer time to diffuse which may result in better crystal quality. Once the Group III materials are applied, Group V material may be applied. The alternation between application of Group

III and Group V material continues until the tunnel junction **112** is complete. Different timeframes may be used when applying the Group III and Group V materials based on the materials used. Alternation times may range anywhere from 1 to 1000 seconds or more.

MEE may allow one to control the V/III ratio and enhance the doping, particularly the dopants like tellurium (Te), sulfur (S), carbon (C), etc., which take the group V atom site. MEE may be run at very low V/III ratio. Particularly when alkyl atoms paralyzed on the surface, Group V is not injected in the chamber, therefore the instant V/III ratio is very low and doping concentration is higher.

Referring to **Figure 4**, concentration light I-V (LIV) curves are shown. In Figure 4, the

light I-V (LIV) performance of an MEE grown HT GaInP tunnel junction is shown versus a conventional epitaxy grown GaInP HT tunnel junction. While the LIV curves of the MEE grown HT GaInP tunnel junction are based on a single junction test structure, it may be clearly seen that the MEE HT TuJn shows higher tunneling current than the conventional epitaxy grown TuJn.

The existing high efficiency multi-junction solar cells normally use the lower temperature

to achieve high doping concentration, particularly with the high bandgap materials like GaInP. MEE can be used for both high and low temperature growth of the TuJn layers and can achieve higher doping and higher quality TuJn layers while the conventional growth will compromise the quality to achieve high doping and therefore compromise the maximum tunneling current, and also the later layer quality. This invention can push the existing TuJn tunnel current to higher value and therefore will improve the efficiency.

As illustrated in the text of this application and the accompanying FIGs. **1-4**, a method is disclosed of forming a tunnel junction **112** in a solar cell structure **100**. The method includes alternating between depositing a Group III material and depositing a Group V material on the solar cell structure **100**. In one variant, alternating between depositing a Group III material and depositing a Group V material includes depositing a Group III material on the solar cell structure **100**, and depositing a Group V material after deposition of the Group III material. In addition, the method may include depositing the Group III material on a first solar cell **108**, e.g., Solar Cell 1, of the solar cell structure **100**. In one variant, the method may include depositing the Group V material on the first solar cell **108** of the solar cell structure **100**. In yet another alternative, the method may include controlling a depositing ratio of the Group III material and the Group V material. In one variant, alternating between depositing the Group III material may include depositing the Group III and the Group V materials for approximately 1 to 1000 seconds. In one alternative, the Group III materials include at least one of: boran (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl). In yet one example, the Group V materials comprise at least one of: nitrogen (N), phosphorus (P), arsenic (As), antimony (Sb), and bismuth (Bi).

As illustrated in the text of this application and the accompanying FIGs. **1-4**, a photovoltaic device is provided including a substrate **102**, a first solar cell **108**, e.g., Solar Cell 1, positioned above the substrate **102**, and a contact **116** positioned above the first solar cell **108**; and a tunnel junction **112** positioned formed between the first solar cell **108** and the contact, wherein the tunnel junction **112** is formed by a migration enhanced epitaxial (MEE) method. In one variant, the tunnel junction **112** is formed by said MEE method of alternating between depositing of Group III and Group V materials. In one example, the Group III materials include at least one of: boran (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl).

In one variant, said Group V materials may include at least one of: nitrogen (N), phosphorus (P), arsenic (As), antimony (Sb), and bismuth (Bi). In addition, the photovoltaic device may include a buffer layer 106 positioned between said substrate **100** and said first solar cell **108**. In addition, the photovoltaic device may include a nucleation layer **104** positioned between said buffer layer **106** and said substrate **102**. In one variant, a second solar cell **114**, e.g., Solar Cell 2, is positioned between said first solar cell **108** and said contact **116**.

While embodiments of the disclosure have been described in terms of various specific embodiments, those skilled in the art will recognize that the embodiments of the disclosure can be practiced with modifications within the spirit and scope of the claims.

What is claimed is:

1. A method of forming a tunnel junction (112) in a solar cell structure (100) comprising alternating between depositing a Group III material and depositing a Group V material on said solar cell structure (100).

2. The method of Claim 1, wherein alternating between depositing a Group III material and depositing a Group V material further comprises:

depositing a Group III material on said solar cell structure (100); and

depositing a Group V material after deposition of said Group III material.

3. The method of any of Claims 1-2, further comprising depositing said Group III material on a first solar cell (108) of said solar cell structure (100).

4. The method of Claim 3, further comprising depositing said Group V material on said first solar cell (108) of said solar cell structure (100).

5. The method of any of Claims 1-4, further comprising controlling a depositing ratio of said Group III material and said Group V material.

6. The method of any of Claims 1-5, wherein alternating between depositing said Group III material further comprises depositing said Group III and said Group V materials for approximately 1 to 1000 seconds.

7. The method of any of Claims 1-6, wherein said Group III materials comprises at least one of: boran (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl).

8. The method of any of Claims 1-7, wherein said Group V materials comprise at least one of: nitrogen (N), phosphorus (P), arsenic (As), antimony (Sb), and bismuth (Bi).

9. A photovoltaic device, comprising:

a substrate (102);

a first solar cell (108) positioned above the substrate (102);

a contact (116) positioned above the first solar cell (108); and

a tunnel junction (112) positioned formed between the first solar cell (108) and the contact (116), wherein the tunnel junction (112) is formed by a migration enhanced epitaxial (MEE) method.

10. A photovoltaic device in accordance with Claim 9, wherein the tunnel junction (112) is formed by said MEE method of alternating between depositing of Group III and Group V materials.

11. A photovoltaic device in accordance with Claim 10, wherein the Group III materials comprise at least one of: boran (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl).

12. A photovoltaic device in accordance with any of Claims 10 or 11, wherein said Group V materials comprise at least one of: nitrogen (N), phosphorus (P), arsenic (As), antimony (Sb), and bismuth (Bi).

13. A photovoltaic device in accordance with any of Claims 9-12, further comprising

a buffer layer (106) positioned between said substrate (102) and said first solar cell (108).

14. A photovoltaic device in accordance with Claim 13, further comprising a nucleation layer (104) positioned between said buffer layer (106) and said substrate (102).

15. A photovoltaic device in accordance with any of Claims 9-14, further comprising a second solar cell (114) positioned between said first solar cell (108) and said contact (116).

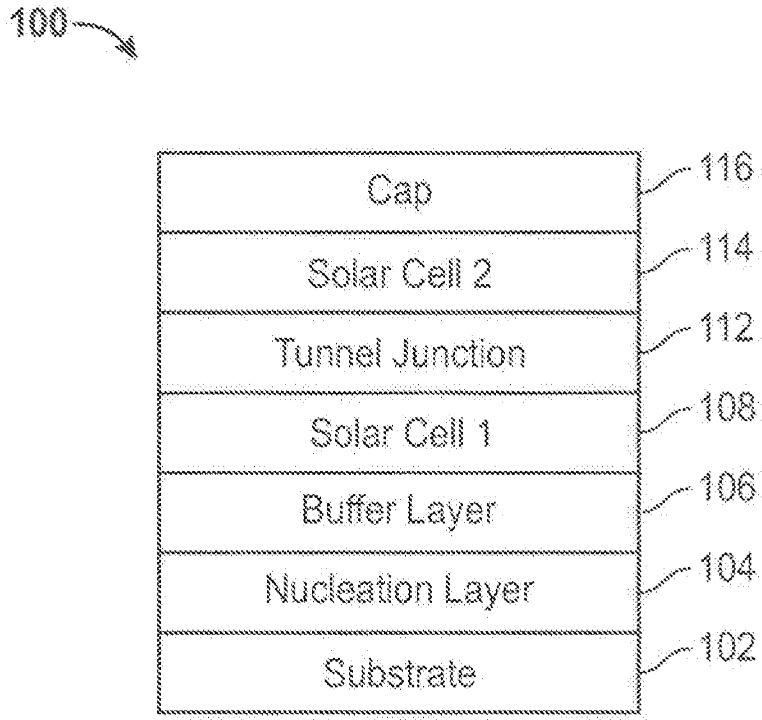
100
Cap
116
Solar Cell 2
114
Tunnel Junction
112
Solar Cell 1
108
Buffer Layer
106
Nucleation Layer
104
Substrate
102

FIG. 1

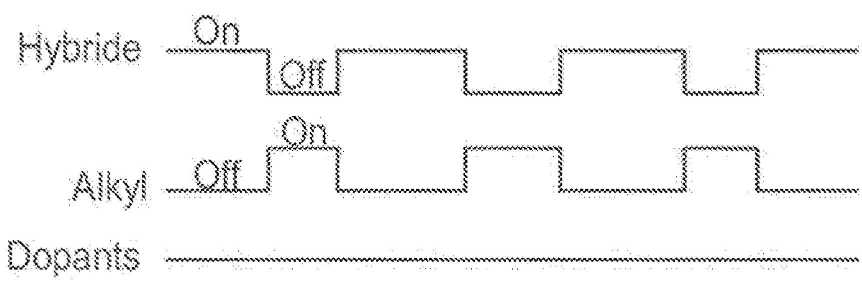
Hybride
On
Off
Alkyl
Off
On
Dopants

FIG. 2

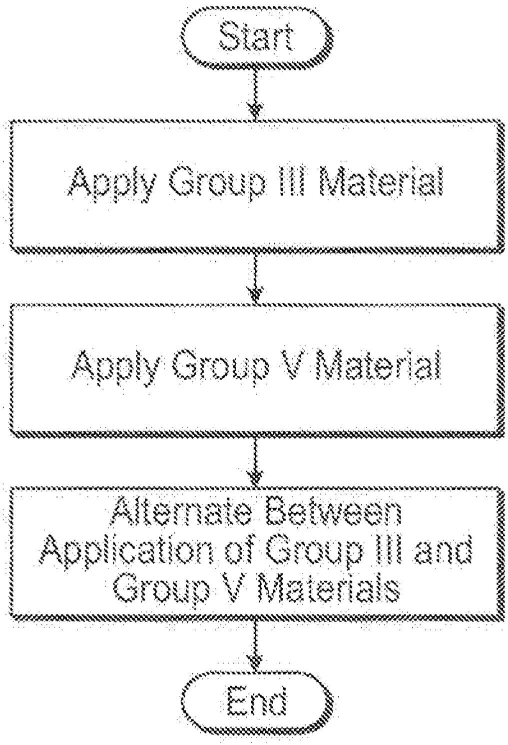
Start
Apply Group III Material
Apply Group V Material
Alternate Between Application of Group III and Group V Materials
End

FIG. 3

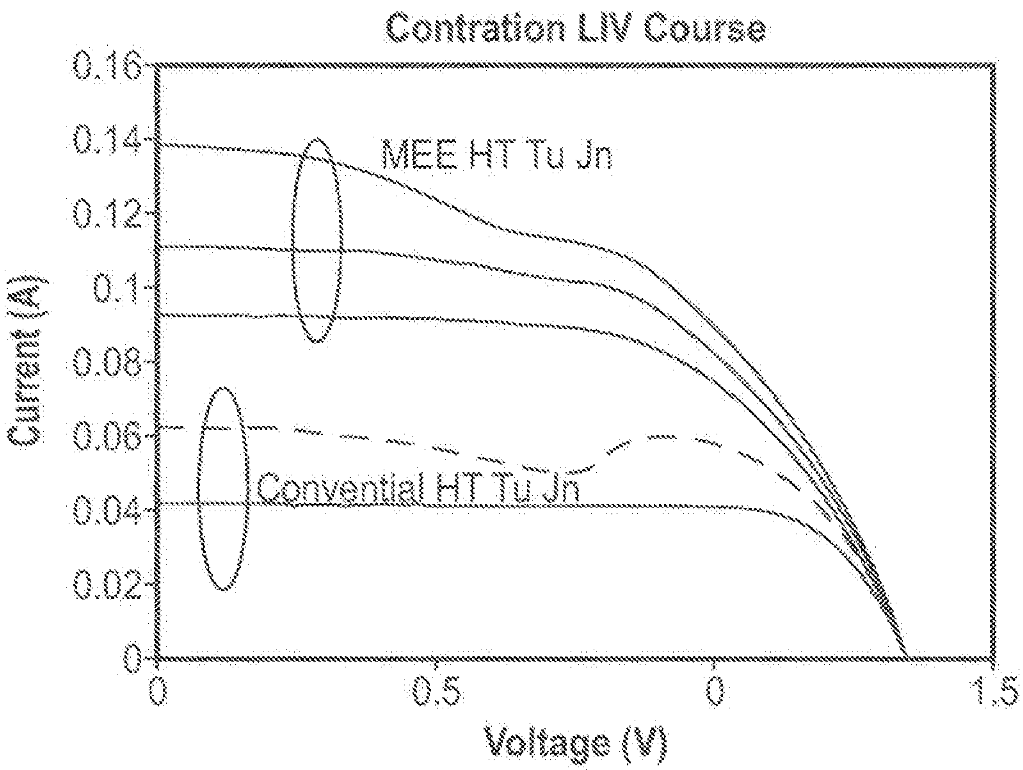
Contration LIV Course
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Current (A)
MEE HT Tu Jn
Convential HT Tu Jn
0
0.5
0
1.5
Voltage (V)

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/030983

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L31/18 H01L31/0687
ADD.

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)
H01L

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)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2004/045598 A1 (NARAYANAN AUTHI A [US] ET AL) 11 March 2004 (2004-03-11) paragraph [0001] - paragraph [0007] paragraph [0037] - paragraph [0053]; figures 1,2,3	1-15

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[X] Further documents are listed in the continuation of Box C.

[X] 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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 July 2012	08/08/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lantier, Roberta

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	RINGEL S A ET AL: "ANTI-PHASE DOMAIN-FREE GAAS ON GE SUBSTRATES GROWN BY MOLECULAR BEAM EPITAXY FOR SPACE SOLAR CELL APPLICATIONS", CONFERENCE RECORD OF THE 26TH IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE - 1997. PVSC '97. ANAHEIM, CA, SEPT. 29 - OCT. 3, 1997; [IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE], NEW YORK, NY : IEEE, US, 29 September 1997 (1997-09-29), pages 793-798, XP001093954, DOI: 10.1109/PVSC.1997.654208 ISBN: 978-0-7803-3767-1 the whole document -----	1-15
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A	CHAVANAPRANEE TOSAPORN ET AL: "Heavily Sn-doped GaAs with abrupt doping profiles grown by migration-enhanced epitaxy at low temperatures", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 100, no. 5, 12 September 2006 (2006-09-12), pages 54505-054505, XP012089962, ISSN: 0021-8979, DOI: 10.1063/1.2338127 the whole document -----	1-15
A	US 2004/084694 A1 (FATEMI NAVID [US] ET AL) 6 May 2004 (2004-05-06) paragraph [0037]; figure 3 -----	1-15
A	ERNST O. GÖBEL, KLAUS PLOOG: "FABRICATION AND OPTICAL PROPERTIES OF SEMICONDUCTOR QUANTUM WELLS AND SUPERLATTICES 3. TECHNOLOGY", PROGRESS IN QUANTUM ELECTRONICS 1990, PERGAMON PRESS, OXFORD, GB, vol. 14, 4, 1 January 1990 (1990-01-01), pages 298-319, XP002680737, ISSN: 0079-6727 paragraph [3.3.4Modulatedbeamflowtechniques]; table 2 -----	1-15

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	HONG Y G ET AL: "Optical properties of GaAs/GaNxAs1-x quantum well structures grown by migration-enhanced epitaxy", JOURNAL OF CRYSTAL GROWTH, ELSEVIER, AMSTERDAM, NL, vol. 242, no. 1-2, 1 July 2002 (2002-07-01), pages 29-34, XP004366239, ISSN: 0022-0248, DOI: 10.1016/S0022-0248(02)01315-5 the whole document -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2012/030983

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004045598 A1	11-03-2004	NONE	
US 2004084694 A1	06-05-2004	AU 2003257168 A1	07-06-2004
		EP 1565944 A1	24-08-2005
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