(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 November 2002 (21.11.2002)

PCT

(10) International Publication Number
WO 02/093658 A1

(51) International Patent Classification⁷: **H01L 33/00**

(21) International Application Number: PCT/US02/15083

(22) International Filing Date: 13 May 2002 (13.05.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/291,757 17 May 2001 (17.05.2001) US

(71) Applicant *(for all designated States except US)*: **EMCORE CORPORATION** [US/US]; 145 Belmont Drive, Somerset, NJ 08873-1214 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **DEBRAY, Jean-Philippe** [FR/US]; 19 Spencer Street, Somerset, NJ 08873 (US).

(74) Agents: MILLET, Marcus, J. et al.; Lerner David Littenberg Krumholz & Mentlik LLP, 600 South Avenue West, Westfield, NJ 07090 (US).

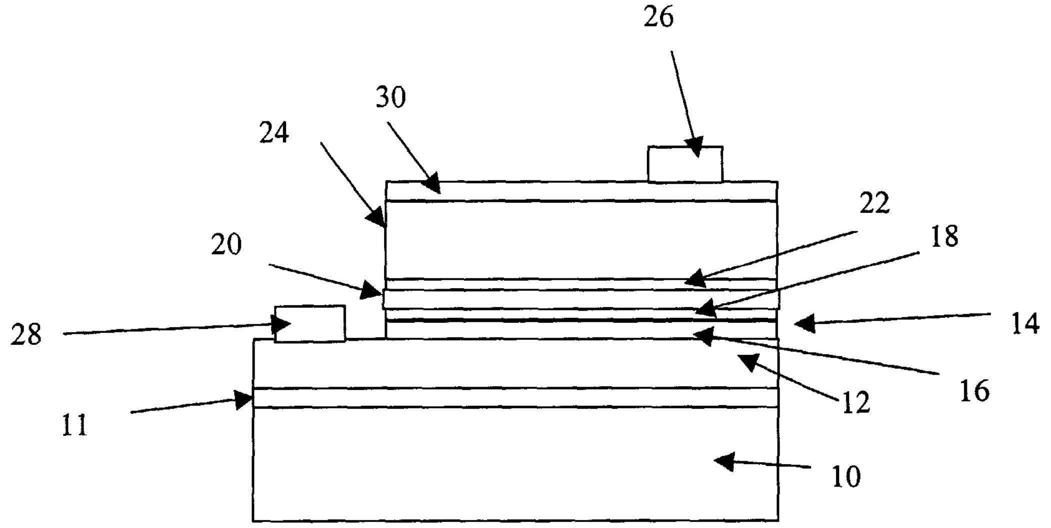
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
- *with international search report*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

[Continued on next page]

(54) Title: NITRIDE SEMICONDUCTOR LED WITH TUNNEL JUNCTION



(57) Abstract: A light emitting diode formed from nitride semiconductors with an active, light-emitting junction (22) including a p-type region (20) incorporates a tunnel junction (14) with a highly-doped p+ layer (18) proximate to the p-type region of the active junction and a highly-doped n+ layer (16) remote from the active junction. A p-side conductive layer (12) formed from n-type nitride semiconductor is conductively connected to the n+ layer (16). An n-side conductive layer (24), also formed from n-type nitride semiconductor is conductively connected to the n-type region of the active junction. Electrodes (26, 28) are conductively connected to the conductive layers (12,24). The tunnel junction (14) is reverse biased during operation. The LED does not require a transparent electrode in contact with p-type nitride semiconductor.

WO 02/093658 A1

NITRIDE SEMICONDUCTOR LED WITH TUNNEL JUNCTION

TECHNICAL FIELD

The present invention relates to light emitting diodes formed from nitride semiconductors such as gallium nitride based semiconductors.

BACKGROUND ART

Light emitting diodes formed from nitride semiconductors can provide certain desirable properties. For example, diodes formed from certain nitride semiconductors emit in the blue and ultraviolet spectral regions.

As used in this disclosure, the term "III-V semiconductor" refers to a material according to the stoichiometric formula AlaInbGacNxAsyPz. In a perfectly stoichiometric III-V semiconductor, $(a + b + c) = (x + y + z) =1.0$. The term "nitride semiconductor" refers to a III-V semiconductor in which x is 0.5 or more, most typically 0.8 or more. The term "pure nitride semiconductor" refers to a nitride semiconductors in which N constitutes essentially all of the Group V atoms in the semiconductor, and hence x is about 1.0. The term "gallium nitride based semiconductor" as used herein refers to a nitride semiconductor including gallium. p-type and n-type conductivity may be imparted to III-V semiconductors by conventional dopants and may also result from the inherent conductivity type of the particular semiconductor material. For example, gallium nitride based semiconductors typically are inherently n-type when undoped. n-type nitride semiconductors may include conventional electron donor dopants such as Si, Ge, S, and O, whereas p-type nitride semiconductors may include conventional electron acceptor dopants such as Mg and Zn.

Semiconductor light emitting diodes or "LEDs" typically include a semiconductor structure having p-type and n-type regions and an active junction between such regions. The structure is typically in the form of layers of material having different compositions, ordinarily formed by epitaxially growing successive layers. The direction through the various layers in the stack is commonly referred to as the vertical direction. The junction between the p-type and n-type material may include directly abutting p-type and n-type layers, or may include one or more intermediate layers which may be of any conductivity type or which may be very thin semi-insulating layers of no distinct conductivity type. The device also includes an electrode in contact with the p-type region and another electrode in contact with the n-type region.

In operation of the LED, a voltage is applied by an external source through the electrodes so that the active junction is forward-biased (n-type region at a negative potential with respect to the p-type region). The applied potential causes a current to flow through the device. The current is carried by electrons and electron vacancies or "holes" which move toward the junction, and recombine with one another at the junction. Energy released by electron-hole recombination is emitted as light. As used in this disclosure, the term "light" includes radiation in the infrared and ultraviolet wavelength ranges, as well as the visible range. The wavelength of the light emitted by an LED depends on factors including the composition of the semiconductor materials and the structure of the active junction.

Most nitride LEDs are formed with a p-type layer at the top of the stack. Because the carrier (hole) mobility in p-type nitride semiconductors is relatively low, the p-type layer exhibits a high resistance to current flow in the horizontal directions. This tends to promote "current crowding", or concentration of the vertical current through the stack in a small region beneath the electrode in contact with the p-type layer. To alleviate this problem, the electrode in contact with the p-type layer extends over substantially the entire top surface, so that conductivity of the electrode promotes horizontal spreading of the current.

The light emitted at the junction must pass out of the LED to be of any use. The light emitted at the junction typically propagates in all directions within the LED, so that emitted light passes to the substrate at the bottom of the LED; to the sides of the LED and to the top of the LED. Thus, it is desirable to assure that light passing to the top of the LED can pass out of the LED. As used herein, the term "top-emitting LED" refers to an LED in which light can pass out of the top surface of the LED. A top-emitting LED optionally may be arranged to emit light through the bottom, through the sides, or both, in addition to emission through the top surface. The electrode of a top-emitting LED is normally substantially transparent to allow light emitted at the active junction to pass out of the device through the electrode. Typically, the electrode will transmit about 80% or more of the light at the emission wavelength impinging on the electrode from the active junction. For example, a conductive transparent electrode with good ohmic contact to p-type gallium nitride can be formed from a high work function metal such as gold, platinum or palladium, most typically gold, in combination with a p-type, transparent oxide semiconductor such as nickel oxide.

However, despite the effort devoted to development of nitride semiconductor LED's, still further improvement would be desirable. For example, the electrode materials which make ohmic contact with p-type nitride semiconductors typically must be formed from different metals than the electrodes which make contact with the n-type semiconductors. This requires additional steps in the manufacturing process. Moreover, a transparent electrode which is not perfectly transparent, and hence absorbs some of the light passing through it. This reduces the amount of useful light reaching the exterior of the die, and thus reduces the external quantum efficiency of the LED. Efforts to minimize this effect by minimizing the thickness of the transparent electrode reduce the conductivity of the transparent electrode and thus reduce its effectiveness in alleviating current crowding.

For these and other reasons, it would be desirable to provide a nitride LED which does not require an electrode in contact with a p-type layer. It would be particularly desirable to provide a top-emitting nitride LED which does not require a transparent electrode on a p-type layer.

SUMMARY OF THE INVENTION

One aspect of the present invention provides a nitride semiconductor LED having n-type nitride semiconductor conductive layers on both sides of the active junction. The n-type conductive layer on the n-side of the active junction is referred to herein as the n-side conductive layer, whereas the n-type conductive layer on the p-side of the active junction is referred to herein as the p-side conductive layer. A tunnel junction is interposed between the p-type layer of the active junction and the p-side conductive layer. The tunnel junction is defined by highly doped p-type ("p+") and n-type ("n+") layers, with the n+ layer disposed on the side of the tunnel junction remote from the active junction. n-side and p-side electrodes are conductively connected to the n-side and p-side conductive layers, respectively. In operation, the n-side electrode, and hence the n-side conductive region is at a negative potential with respect to the p-side electrode and p-side conductive region, so that the active junction is forward-biased whereas the tunnel junction is reverse biased. Because a tunnel junction conducts with low resistance in the reverse-bias mode, it does not substantially impede current flow through the device or appreciably increase the power consumption of the device.

The p-side conductive layer provides substantial horizontal conductivity on the p-side of the active junction. Accordingly, there is normally no need for a conductive electrode overlying the entire top surface of the device.

Moreover, because both the p-side and n-side electrodes are connected to conductive layers formed from n-type nitride semiconductor materials, both of these electrodes may be formed from the same material, such material being selected to provide good ohmic contact with the n-type semiconductor. Because both electrodes can be formed from the same material, the electrode-forming process is simplified.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic side elevational view of an LED according to one embodiment of the invention.

FIG. 2 is a diagrammatic side elevational view of an LED according to another embodiment of the invention.

BEST MODE FOR CARRYING OUT INVENTION

An LED in accordance with one embodiment of the invention includes a stacked structure of semiconductor layers on a substrate 10 as, for example, sapphire (Al_2O_3). The stacked structure includes a p-side conductive layer 12 formed from n-type nitride semiconductor material overlying the substrate. A buffer layer or nucleation layer 11 is provided between the substrate and conductive layer 12 to compensate for lattice mismatch between the substrate and the semiconductor of layer 12. For example, where layer 12 is formed from GaN, the buffer layer may be polycrystalline GaN or AlGaN deposited at a relatively low temperature prior to deposition of the conductive layer 12. The n-type material in conductive layer 12 is a conventional n-type nitride semiconductor formulated to provide good electrical conductivity. Where the n-type material is GaN, it desirably is doped to provide a carrier concentration on the order of $4 \times 10^{18} cm^{-3}$, and typically has a carrier mobility of at least about 200 cm^2/Vs. A tunnel junction 14 includes a n+ layer 16 conductively connected to the p-side conductive layer 12 and a p+ layer 18 abutting the n+ layer. The n+ layer and p+ layers are highly doped, so that each of these layers has a carrier concentration of at least about $5x10^{18}cm^{-3}$. Thus, these layers define a very thin depletion region between them, typically on the order of a few hundred Angstroms or less.

A p-type layer 20 is conductively connected to the p+ layer. This p-type layer forms the p-type region of the active junction 22. The n-type region of the active junction 22 is defined by an n-side conductive layer 24, which may have substantially the same composition as the p-side conductive layer 12. The active junction 22 is symbolized in Fig. 1 as a discrete active layer interposed between p-type layer 20 and n-side conductive layer and 16. In a preferred embodiment, the active layer includes a multiple quantum well structure incorporating numerous thin barrier layers and well layers, the well layers having smaller band gap than the barrier layers. For example, the well layers may be InGaN whereas the barrier layers may be GaN. p-type layer 20 desirably has larger band gap than the active layer, so that the p-type layer serves as a clad layer to promote carrier confinement. The material constituting a single or multiple layer or layers may be doped or undoped in accordance with conventional practice. Other conventional types of active junctions can be used. For example, layers 20 and 24 may abut one another so that they define the junction at their mutual border. Alternatively, a single active layer of uniform composition can be used in place of the multiple quantum well structure. Each of the various layers may include additional layers of different compositions but of the same conductivity type. Thus, the active junction may be a simple homojunction; a single heterojunction, a double heterojunction, a single quantum well, a multiple quantum well or any other type of junction structure.

An n-side electrode 26 is connected to with the n-side conductive layer 24, whereas a p-side electrode 28 is connected to p-side conductive layer 12. Desirably, the electrodes make ohmic contact with the conductive layers either directly or through intervening layers. To promote ohmic contact, the n-side conductive layer 24 may include a highly doped n++ layer 30 at the top surface abutting electrode 26. Also, the p-side conductive layer may include a similar n+ layer (not shown) beneath electrode 28. Alternatively, the n+ layer 16 of the tunnel junction may extend beneath electrode 28. Most preferably, the n-side contact 26, at the top of the device, does not entirely cover the top surface. One suitable material for ohmic contact with n-type GaN includes titanium and aluminum, which may be deposited as separate layers or as an alloy, and which are annealed after deposition. The electrodes can be connected to conductors such as wire bonds, leads or circuit traces (not shown) which serve to connect the electrodes, and hence the LED, to external circuitry. The electrodes may also include additional metals as, for example, platinum and gold layers, to facilitate wire bonding or soldering to such conductors. The additional metals may be provided on the entire electrode or on a region of the electrode which serves as the bonding pad.

In operation, when n-side terminal 26 is at a negative potential with respect to p-side terminal 28, active junction 22 is forward-biased whereas tunnel junction 20 is reverse-biased. The conductivity of layers 12 and 24 promotes current spreading in the horizontal directions, so that the current flow in the vertical direction through the active junction 22 is substantially uniform over the horizontal extent of the active junction. Light emitted at the active junction passes out of the device through the upper or n-side conductive layer 24, and may also pass out of the device through the edges of the stack and through the substrate 10. The conductive layers, and particularly the conductive layer 24 disposed above the active junction, should have band gap larger than the band gap of the emitting material at active junction 22 so that they will be transparent to the emitted light. The electrode configurations may be selected to further promote current spreading. For example, the contact configurations disclosed in co pending, commonly assigned United States Patent Application 09/692,953, the disclosure of which is hereby incorporated by reference herein, may be used. In embodiment disclosed in the '953 Application, an LED has a top electrode or pad on a mesa and a lower electrode in the form of a ring encircling the mesa. In the structure discussed above with reference to Fig. 1, the p-side electrode 28 can completely or partially encircle a mesa which includes the n-side conductive layer 24. In such an arrangement, the n-side electrode 26 can be disposed at or near the center of the top surface of the n-side conductive layer.

Known fabrication processes can be used to form the stacked structure. The various layers constituting the stacked structure typically are grown on the substrate while the substrate is part of a larger wafer, and the various layers cover the entire wafer. The wafer is later subdivided to form individual pieces or "dies". Most commonly, the various layers which form the stacked structure are deposited on the substrate in sequence by techniques such as metal organic chemical vapor deposition ("MOCVD") molecular beam epitaxy and the like.

A LED according to a further embodiment of the invention, depicted in Fig. 2, is generally similar to the LED discussed above. However, the positions of the n-side and p-side conductive layers are reversed, so that the n-side conductive layer 124 is disposed adjacent the bottom of the stack, near substrate 120, whereas the p-side conductive layer 112 is disposed adjacent the top of the stack. The p-type layer 120 of active junction 122 thus lies on the top side of the active junction. The tunnel junction 114 is disposed above the active junction 120. The n+ layer 116 of tunnel junction 114 is disposed above the p+ layer 118 of the tunnel junction.

In still other embodiments, more than one active junction can be provided, stacked one above the other.

The LED’s shown in Figs. 1 and 2 are top-emitting LED’s. Thus, the light emitted at the junction can pass out of the top surface defined by layer 30 included in the n-side conductive layer 24 (Fig. 1) or out of the top surface defined by the p-side conductive layer 112 (Fig. 2). However, the invention can be employed in other arrangements. For example, the top surface of the LED may be reflective. In one such arrangement, the substrate is transparent and the electrode on the top surface of the die is a thick, reflective metallic electrode covering all or most of the top surface. Such a die can be mounted in "flip-chip" orientation, with the top surface facing toward a circuit board or other mounting structure, and with the transparent substrate exposed so that light emitted through the transparent substrate can pass out of the die.

As these and other variations and combinations of the features discussed above can be utilized without departing from the present invention, the foregoing description of the preferred embodiments should be taken by way of illustration rather than by way of limitation of the invention.

INDUSTRIAL APPLICABILITY

LED’s according to the present invention can be utilized as light sources in displays such as computer terminal displays; in lamps; as indicators; as sources of ultraviolet light for exciting phosphors in lamps and displays; and in numerous other applications.

CLAIMS

1. A nitride semiconductor LED comprising a stack of semiconductor layers, said stack including p-type and n-type regions defining a p-n active junction having a p-side and an n-side;

an n-side conductive layer of n-type nitride semiconductor on the n-side of the active junction conductively connected to the n-type region of the active junction,

a p-side conductive layer of n-type nitride semiconductor on the p side of the active junction;

a tunnel junction interposed between the p-type layer of the active junction and the p-side conductive layer, said tunnel junction including a p+ layer of highly doped p-type nitride semiconductor disposed on a side of the tunnel junction proximate to the active junction and an n+ layer of highly doped n-type nitride semiconductor disposed on the side of the tunnel junction remote from the active junction, said n+ layer being conductively connected to the p-side conductive layer, said p+ region being conductively connected to the p-type region of the active junction.

2. An LED as claimed in claim 1 further comprising an n-side electrode conductively connected to the n-side conductive layer and a p-side electrode conductively connected to the p-side conductive layer.

3. An LED as claimed in claim 2 wherein said n-side conductive layer defines a top surface of the stack and said LED is adapted to emit light through said top surface.

4. An LED as claimed in claim 3 wherein said n-side electrode extends on a part of said top surface but does not cover the entire top surface.

5. An LED as claimed in claim 2 wherein said p-side conductive layer defines a top surface of the stack and said LED is adapted to emit light through said top surface.

6. An LED as claimed in claim 5 wherein said p-side electrode extends on a part of said top surface but does not cover the entire top surface.

7. An LED as claimed in claim 2 wherein said p-side and n-side electrodes are formed from the same material.

8. An LED as claimed in claim 1 wherein said p-side and n-side conductive layers have a carrier concentration of at least about $4x10^{18}cm^{-3}$ and a carrier mobility of at least about 200 cm^2/Vs.

9. An LED as claimed in claim 1 wherein said p+ and n+ layers have carrier concentrations of at least about $5x10^{18}cm^{-3}$

10. An LED as claimed in claim 1 wherein at least some of said semiconductor layers are formed from gallium nitride based semiconductors.

11. An LED as claimed in claim 1 wherein said and conductive layers are formed from gallium nitride based semiconductors, the LED further comprising electrodes formed from a combination of Ti and Al in ohmic contact with said conductive layers.

12. An LED as claimed in claim 1 wherein a part of said n-side conductive layer forms said n-type region of said active junction.

13. A method of producing light comprising the step of applying an electrical potential to an LED as claimed in any of the preceding claims so that said n-side conductive layer is at a negative potential with respect to said p-side conductive region, whereby said tunnel junction is reverse-biased and said active junction is forward-biased.

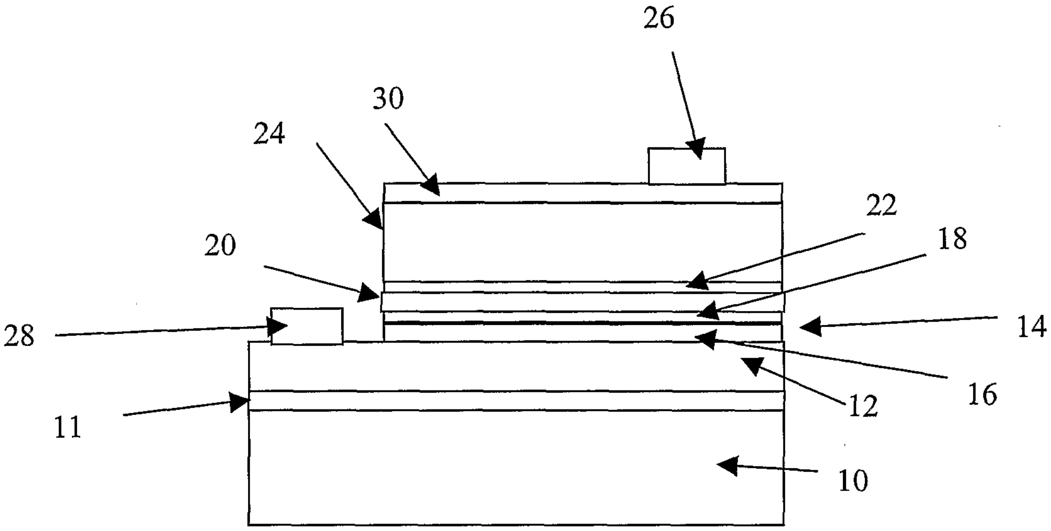


FIG. 1

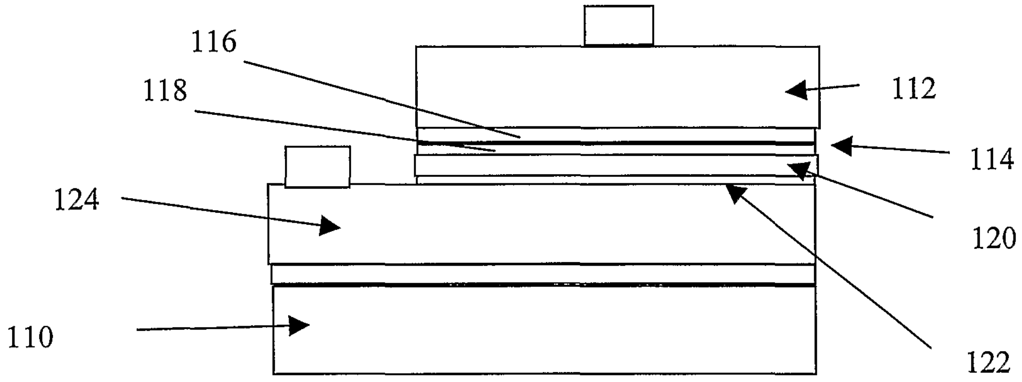


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/15083

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01L 33/00
US CL : 257/103

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)
U.S. : 257/25,30,46,101,102

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
E.AS.T. using search string "(tunnel$4 near diode) and (led or light adj emitting)"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 07-297448 A (HITACHI LTD) 10 November 1995 (10.11.1995), paragraphs 13, 19-22, drawing 5.	1-6,10-13
Y	US 5981980 A (MIYAJIMA, et al.) 09 November 1999 (09.11.1999), column 7 lines 48-58, 66-67, figure 1.	1-6,10-13

☐ 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

"E" earlier application or patent published on or after the international filing date

"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)

"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

"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

"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

"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

"&" document member of the same patent family

Date of the actual completion of the international search 16 July 2002 (16.07.2002)	Date of mailing of the international search report 1[illegible] SEP 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Shawn S. Hoppe Thomas L Dickey Telephone No. (703) 308-0956

Form PCT/ISA/210 (second sheet) (July 1998)