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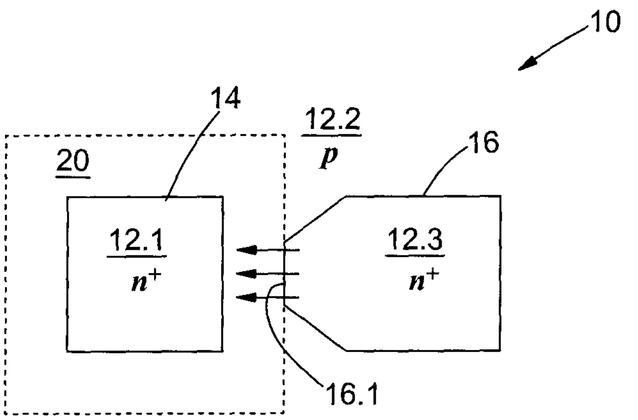

FIGURE 5

(57) Abstract: A light emitting device (10) comprises a body (12) of a semiconductor material. A first junction region (14) is formed in the body between a first region (12.1) of the body of a first doping kind and a second region (12.2) of the body of a second doping kind. A second junction region (16) is formed in the body between the second region (12.2) of the body and a third region (12.3) of the body of the first doping kind. A terminal arrangement (18) is connected to the body for, in use, reverse biasing the first junction region (14) into a breakdown mode and for forward biasing at least part (16.1) of the second junction region (16), to inject carriers towards the first junction region (14). The device (10) is configured so that a first depletion region (20) associated with the reverse biased first junction region (14) punches through to a second depletion region associated with the forward biased second junction region (16).

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SEMICONDUCTOR LIGHT EMITTING DEVICE UTILISING PUNCH-THROUGH EFFECTS

INTRODUCTION AND BACKGROUND

This invention relates to optoelectronic devices and more particularly to a light emitting device fabricated from a semiconductor material and to a method of generating light in a semiconductor material.

Avalanche electroluminescent light emission in single crystal indirect bandgap semiconductors (e.g. silicon) is generated by the interaction between mobile carriers (e.g. recombination of electrons and holes) and lattice phonons in a reverse biased pn junction. The internal quantum efficiency (number of photons generated per electron) can be enhanced if "cool" (low energy) carriers are injected into the reverse biased junction from a closely spaced forward biased junction to interact with the "hot" energetic carriers within the depletion region.

However, in conventional devices, the carriers injected from the forward biased junction will be injected across all of the forward biased junction area (sidewalls and bottom wall). This means that only a relatively small percentage of all the injected carriers reach the reverse biased depletion region, to initiate light generation. The carriers not reaching the reverse biased avalanching depletion are lost and represent device current not being utilized for light generation, thus reducing the power efficiency of the light source.

OBJECT OF THE INVENTION

Accordingly, it is an object of the present invention to provide an alternative light emitting device and associated method with which the applicant believes the aforementioned disadvantages may at least be alleviated.

SUMMARY OF THE INVENTION

According to the invention there is provided a light emitting device comprising;

- a body of a semiconductor;
- a first junction region in the body formed between a first region of the body of a first doping kind and a second region of the body of a second doping kind;
- a second junction region in the body formed between the second region of the body and a third region of the body of the first doping kind;
- a terminal arrangement connected to the body for, in use, reverse biasing the first junction region into a breakdown mode and for forward biasing at least part of the second junction region, to inject carriers towards the first junction region; and

- the device being configured so that a first depletion region associated with the reverse biased first junction region punches through the second region to a second depletion region associated with the forward biased at least part of the second junction region.

The semiconductor material may be an indirect bandgap material. Alternatively it may be a direct bandgap material.

The breakthrough mode may be an avalanche mode, alternatively a field emission mode, further alternatively a combination of avalanche and field emission.

In some embodiments the first doping kind may be n and the second doping kind may be p. In other embodiments the first doping kind may be p and the second doping kind may be n.

In some embodiments the first depletion region may punch through to the second junction region.

The terminal arrangement may comprise two terminals, a first terminal connected to the first region of the body, to apply a voltage of a first polarity to the first region; and a second terminal connected to the third region of the body, to apply a voltage of an opposite polarity to the third region.

Alternatively, the terminal arrangement may comprise three terminals, a first terminal connected to the first region of the body; a second terminal connected to the third region of the body; and a third terminal connected to the second region of the body. A modulation signal may be applied to the third terminal. Hence, the first and second termainals may be used for controlling electroluminescence processes, carrier energies and carrier density profiles; and the third terminal may be used for controlling the modulation of the output electroluminescence of the device .

The invention further includes in its scope a method of operating a light emitting device comprising the steps of:

- utilizing a body of a semiconductor material;
- causing a first junction region to be formed between a first region of the body of a first doping kind and a second region of the body of a second doping kind and a second junction region to be formed in the body between the second region

of the body and a third region of the body of the first doping kind;

- reverse biasing the first junction region into a breakdown mode;
- causing at least part of the second junction region to be forward biased, to inject carriers towards the first junction region; and
- causing a first depletion region associated with the reverse biased first junction region to punch through the second region of the body to a second depletion region associated with the forward biased second junction region.

The second junction may be slightly reverse biased and the first part of the second junction region may be caused to be forward biased by the punched through first depletion region.

BRIEF DESCRIPTION OF THE ACCOMPANYING DIAGRAMS

The invention will now further be described, by way of example only, with reference to the accompanying diagrams wherein:

figure 1 is a diagrammatic representation of a silicon light emitting device;

figure 2 is a schematic diagram of the layout in plan of a conventional silicon carrier injection light emitting device;

figure 3 is a schematic section on line III in figure 2;

figure 4 is a energy band diagram for the conventional device in figures 2 and 3;

figure 5 is a diagram similar to figure 2 for the device in accordance with the invention;

figure 6 is an energy band diagram for the carrier injection device in accordance with the invention;

figure 7 is a diagrammatic representation of a two terminal device in accordance with the invention;

figure 8 is a diagram of carrier concentration profiles in a conventional n^+p diode;

figure 9 is a similar diagram in a punch through n^+pn^+ device in accordance with the invention;

figure 10 is a schematic diagram of an alternative embodiment of the device according to the invention;

figure 11 is a diagram of electrical field strength and distribution fo the device in figure 10;

figure 12 is an alternative representation of the device in figure 10;

figure 13 is a diagrammatic representation of carrier energy against distnce for the device in figure 10;

figure 14 is a diagram of carrier concentration against distance for the device in figure 10; and

figure 15 is a Si band diagram illustrating possible and different photonic energy transitions.

DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

A multi-terminal light emitting device fabricated from a semiconductor material is generally designated by the reference numeral 10 in figure 1. The material may be an indirect bandgap semiconductor material, such as Si, Ge and Si-Ge. In other embodiments, a direct bandgap material may be used.

In the embodiment shown, the device 10 comprises a body 12 of an indirect bandgap semiconductor material, in this case Si. The body comprises a first junction region 14 between a first region 12.1 of the body of a first doping kind and a second region 12.2 of the first body of a second doping kind. The first body further comprises a second junction region 16 between the second region 12.2 and a third region 12.3 of the body, also of the first doping kind. The first doping kind may be n^+ and the second doping kind may be p. In other embodiments opposite doping kinds may be used. A terminal arrangement 18 is connected to the body for, in use, reverse biasing the first junction region 14 into a breakdown mode and for forward biasing at least part of the second junction region 16, to inject carriers towards the first junction region. The breakdown mode may be an avalanche mode, alternatively a field emission mode, further alternatively a combination of avalanche and field emission.

Referring now also to figure 5, the device 10 is configured so that a first depletion region 20 associated with the reverse biased first junction region 14 punches through to a second depletion region associated with the forward biased second junction region 16. In the embodiment shown in figure 5, the first depletion region 20 punches through to at least first part 16.1 of the second junction region 16.

Referring to figures 2 and 3, in conventional devices 100, carriers 102 injected into the p-type material 112.2 will be injected across all of the forward biased junction region 116, including the sidewalls 116.1 and bottom wall 116.2 thereof. This means that only a relatively small percentage 102.1 of all the injected carriers 102 reach the reverse biased depletion region 120 to initiate light generation. The carriers not reaching the reverse biased avalanching depletion will be lost and represent device current not being utilized for light generation, thus reducing the power efficiency of the light source.

On the other hand, it is believed that with a punch through structure, such as that shown in of figure 5, the percentage of injected carriers reaching the avalanching reverse biased junction 14 is increased.

The energy diagram shown in figure 4 presents the energy barriers of the two junctions 114 and 116 in a conventional device 100 as shown in figures 2 and 3. The barrier of the reverse biased junction 114 is increased from the equilibrium condition, while the barriers of the forward biased junction 116 is reduced compared to the equilibrium (zero volt bias) condition. The width of depletion region 120 of the reversed bias junction 114 is indicated at 122 and the energy barrier of the forward biased junction 116 is indicated at 124 in figure 4.

Referring now again to figure 5, it is believed that if the depletion region 20 of the reverse biased junction 14 can be made to reach the depletion region of the forward biased junction 16, the electrostatic influence of the reverse biased junction 14 will lower the energy barrier (shown at 24 in figure 6) at the forward biased junction 16 locally at 16.1, only where the depletion regions meet, compared to that of the conventional device as shown at 124 in figure 4.

As shown in figure 6, the energy barrier 24 at the forward biased junction is even further lowered by the encroaching depletion region 20 from the reverse biased junction 14. This effect is commonly known as punch through, normally seen as a negative parasitic effect, but in this case the effect is used in a positive way to enhance avalanche electroluminescence effects.

The punch through effect can be localised as shown at 16.1 in figure 5. In the device in figure 5, the reverse biased junction depletion region 20 punches through to the laterally spaced nearby junction 16 in a localized, well defined, part or interface 16.1. The nearby junction energy barrier 24 is lowered locally at the intersection interface 16.1, causing that part 16.1 of the junction 16 to be more forward biased than the rest of the junction area. In practice, the nearby junction 16 can in fact be slightly reverse biased to stop carrier injection entirely across all of the nearby junction area. In this case, the punch through interface 16.1 will be the only part of the nearby junction being forward biased by the energy barrier lowering effect, causing exclusive carrier injection into the reverse biased junction depletion region. It is believed that by using the device in this mode, there may be less losses as a result of carrier injection into the bulk not reaching the reverse biased depletion region, and it is further believed that electroluminescence efficiency may be improved.

As shown in figure 7, the carrier injection punch through device 10 in accordance with the invention, may also be operated as a two terminal device. In this mode of operation, the p-type bulk contact of the terminal arrangement 18 is not necessary.

The advantage of using carrier injection into the avalanching junction can be demonstrated by investigating the carrier concentration profiles in the depletion region for a conventional n^+p junction, compared to the punch through n^+pn^+ structure.

The carrier concentration profile for the conventional n^+p junction in avalanche breakdown is shown in figure 8 and the carrier concentration profile for the punch through n^+pn^+ structure is shown in figure 9.

The device represented in figure 8 has a relatively wide depletion region, high avalanche gain and low electron carrier concentration on the depletion region edge next to the p-region. The carriers to be avalanche multiplied are thermally generated in the p-region, and constitute a small thermally generated leakage current. The avalanche gain must be high to increase this small leakage current to a relatively large reverse avalanche current to generate light.

On the other hand, in the case of the punch through device 10 represented in figure 9, the current to be avalanche multiplied is the injection current from the forward biased junction 16, which is much higher than the thermally generated leakage current. In this device the avalanche gain needed should be less to attain the same light generating current, causing the depletion region 20 to be narrower, resulting in shorter transit time of carriers through the device 10 and thus faster switching response. The narrower depletion region 20 may also result in a lower operating voltage, resulting in improved power efficiency of the light generating process.

Also evident from figure 9 is the significantly higher carrier concentration of the electrons in the punch through case, which may lead to a higher probability of carrier-phonon and carrier-carrier radiative interactions to occur within the high electric field depletion region, especially if direct radiative carrier (electron-hole) recombination is proportional to the electron/hole carrier concentration pn product.

Another advantage of the punch through device 10 may be that at the point of carrier injection form the forward biased junction 16, i.e. near the forward biased junction, large numbers of "cool" (low energy) electrons are in the same volume region of the depletion region 20 with large numbers of accelerated "hot" (energetic) holes, which will enhance the radiative direct bandgap carrier recombination process.

In figure 10 there is shown a diagrammatic representation of an alternative device according to the invention in the form of a p^+np^+ avalanche injection silicon electroluminescent device 10. In figure 11, a diagram of electrical field strength and distribution through the device 10 is given. Near a first p^+n junction 14 the electric filed conditions reach high enough magnitudes to allow ionization and multiplication of host atoms. This region is referred to as the excitation zone. Because of the ionization of host atoms in the centre n region, the electric field strength gradually decays until it reaches the second p^+n junction 16. The region between the two junctions is referred to as the drift zone 30. The remaining short electric field decay is taken up by ionization of host dopant atoms in the highly doped p^+ region 12.3. Because of the specific bias conditions and as illustrated in figure 12, a large density of low energy (cool) holes is injected from the second p^+n junction 16, also referred to as the injection zone, into the drift zone 30.

A distribution of both excited high energy electrons is formed at the excitation junction 14. These electrons traverse through the drift zone 30 of the device. During their traverse they may interact with defect centers that may act as recombination or relaxation centers. Since large densities of holes are injected from the injection zone 16 and which travel in a direction opposite to that of the electrons, recombination may occur between high energy drifting electrons and lower energy injected holes in the whole of the drift zone 30.

Representations of carrier energy for both electrons and holes as they traverse the drift region 30 are shown in figure 13. Excited electrons traverse through the drift zone 30 substantially maintaining their maximum ionization energy for host atoms, which is approximately 1.8eV. The electric field strength is high enough to sustain this energy for the electrons throughout the drift region. When they reach the punch through interface (the interface where the depletion region 20 and injecting junction depletion region meet), it can be assumed that the electrons penetrate the injection zone and even maintain their energy until the end of the injection zone depletion region. Since high energy electrons have an average mean free path length of about 150nm before losing their energy, most of the electrons will penetrate also the almost neutral p^+ region 12.3 of the injection junction. Here they may subsequently interact with a large number of free low energy holes as present in the p^+ region 12.3. The holes being injected into the drift zone from the injecting p^+n junction gain energy fast and it is assumed that they gain maximum ionization energy for holes of host silicon of approximately 2.3eV within 150 to 200nm. The holes maintain their energy as they traverse the rest of the drift zone 30. Recombination processes between high energy electrons and medium and high energy holes may occur throughout the drift zone, but may have minor implication on the energy and carrier distribution.

Figure 14 shows the corresponding projected carrier density profiles for electrons and holes as they traverse the drift zone 30. Because of the high field strength in the drift zone 30, the electrons traverse the zone with high speed (near saturation velocity), without much decrease in carrier density. When they interact and recombine with large densities of injected holes from the injecting junction 16, it can be assumed that their concentration may rapidly decay until all electrons has recombined with holes. This process may occur mainly in the last part of the drift zone 30 and even into the neutral p^+ region. Similarly, high densities of low energy holes are injected from the junction 16 and interact with the traversing high energy exiting electrons. It can hence be assumed that the hole concentration rapidly decays from the junction 16 to certain moderate levels. Once in the high electric field drift zone 30, they reach saturation velocity and drift with lesser recombination through the rest of the drift zone. It is presently expected that particularly favorable regions for maximum electroluminescent yield would be near the injection zone 16, where the densities for both traversing high energy electrons as well as injected low energy holes are high. Considering the corresponding projected energies of the carries as represented in figure 13, it is presently expected that transitions of type D as represented in figure 15 and leading to energy transitions of respectively 2.3eV and 0.5eV may occur. Deeper into the drift region 30, transitions of type C of approximately 2.8 to 2.9eV may occur. Transitions of type A and B may occur in still deeper regions of the drift zone closer to junction 14.

CLAIMS

1. A light emitting device comprising;
   - a body of a semiconductor material;
   - a first junction region in the body formed between a first region of the body of a first doping kind and a second region of the body of a second doping kind;
   - a second junction region in the body formed between the second region of the body and a third region of the body of the first doping kind;
   - a terminal arrangement connected to the body for, in use, reverse biasing the first junction region into a breakdown mode and for forward biasing at least part of the second junction region to inject carriers towards the first junction region; and
   - the device being configured so that a first depletion region associated with the reverse biased first junction region punches through to a second depletion region associated with the forward biased at least part of the second junction region.

2. A light emitting device as claimed in claim 1 wherein the semiconductor material is an indirect bandgap semiconductor material.

3. A light emitting device as claimed in claim 1 wherein the semiconductor material is a direct bandgap semiconductor material.

4. A light emitting device as claimed in any one of claims 1 to 3 wherein the first doping kind is n and the second doping kind is p.

5. A light emitting device as claimed in any one of claims 1 to 3 wherein the first doping kind is p and the second doping kind is n.

6. A light emitting device wherein the breakdown mode is one of an avalanche mode, a field emission mode and a combination of avalanche and field emission.

7. A light emitting device as claimed in any one of claims 1 to 6 wherein the first depletion region punches through to the second junction region.

8. A light emitting device as claimed in any one of claims 1 to 7 wherein the terminal arrangement comprises two terminals, a first terminal connected to the first region of the body to apply a voltage of a first polarity to the first region and a second terminal connected to the third region of the body to apply a voltage of an opposite polarity to the third region.

9. A light emitting device as claimed in any one of claims 1 to 7 wherein the terminal arrangement comprises three terminals, a first terminal being connected to the first region of the body to apply a voltage of a first polarity to the first region of the body, a second terminal being connected to the third region of the body to apply a voltage of an opposite polarity to the third region and a third terminal being connected to the second region of the body.

10. A method of operating a light emitting device comprising the steps of:

- utilizing a body of a semiconductor material;
- causing a first junction region to be formed between a first region of the body of a first doping kind and a second region of the body of a second doping kind and a second junction region to be formed in the body between the second region of the body and a third region of the body of the first doping kind;
- reverse biasing the first junction region into a breakdown mode;
- causing at least a first part of the second junction region to be forward biased, to inject carriers towards the first junction region; and
- causing a first depletion region associated with the reverse biased first junction region to punch through the second region of the body to a second depletion region associated with the forward biased at least first part of the second junction region.

11. A method as claimed in claim 10 wherein the second junction region is slightly reverse biased and the first part of the second junction region is caused to be forward biased by the punched through first depletion region.

12. A method as claimed in claim 10 or claim 11 wherein the semiconductor material is an indirect bandgap semiconductor material.

13. A method as claimed in claim 10 or claim 11 wherein the semiconductor material is a direct bandgap semiconductor material.

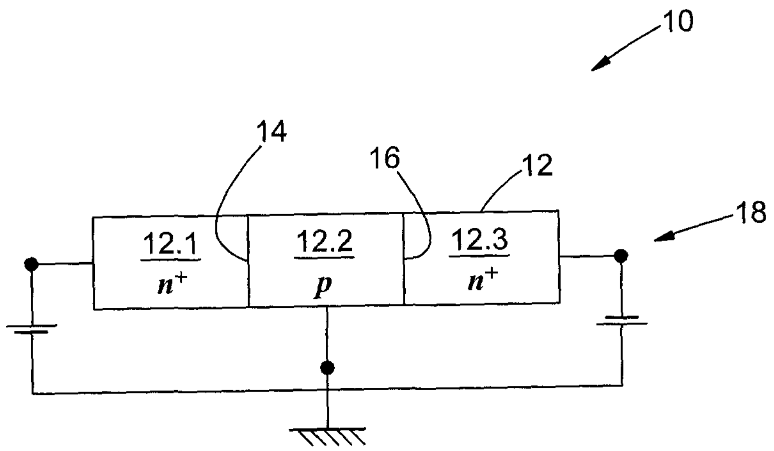

FIGURE 1

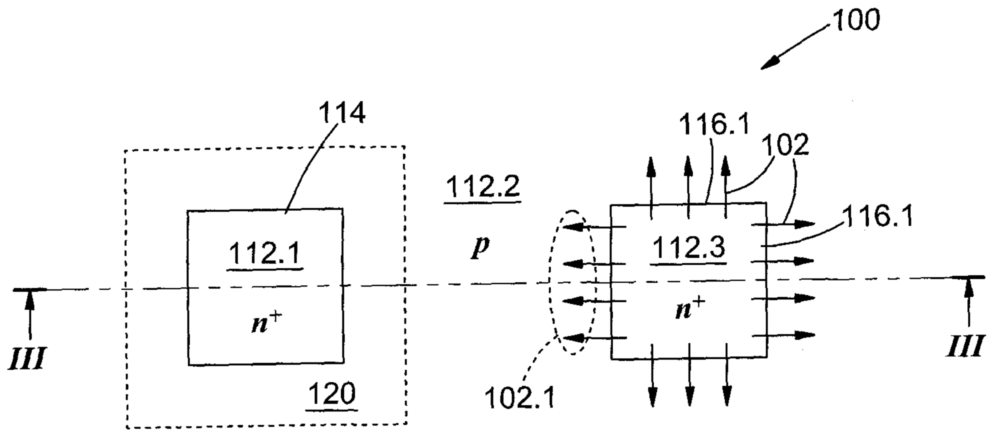

FIGURE 2 (PRIOR ART)

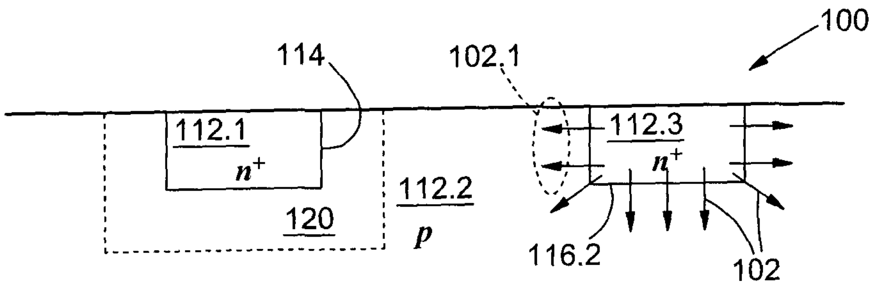

FIGURE 3 (PRIOR ART)

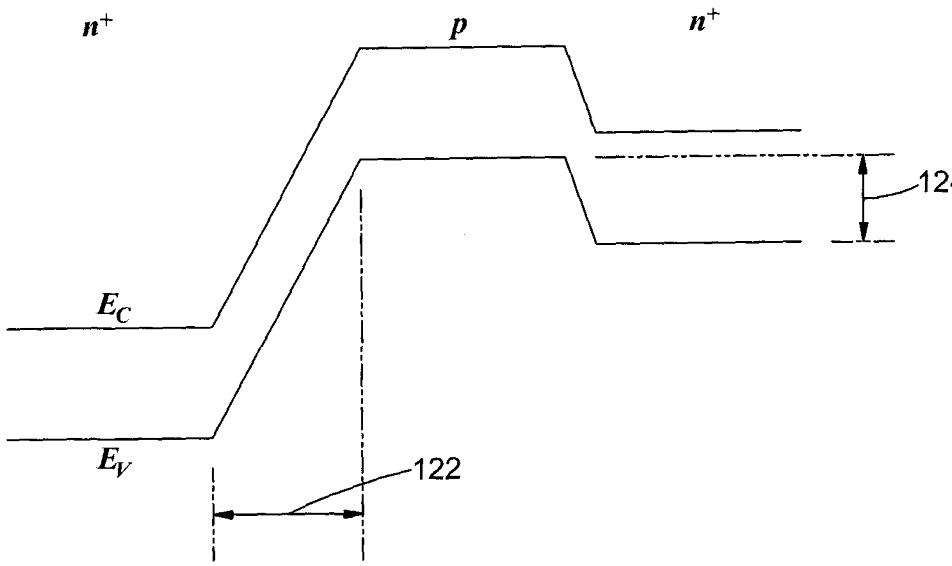

FIGURE 4 (PRIOR ART)

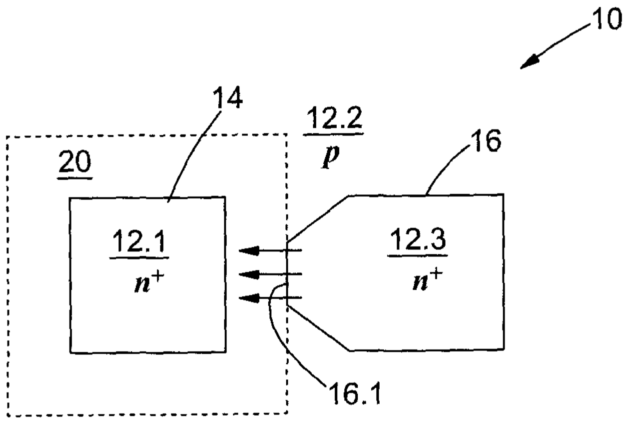

FIGURE 5

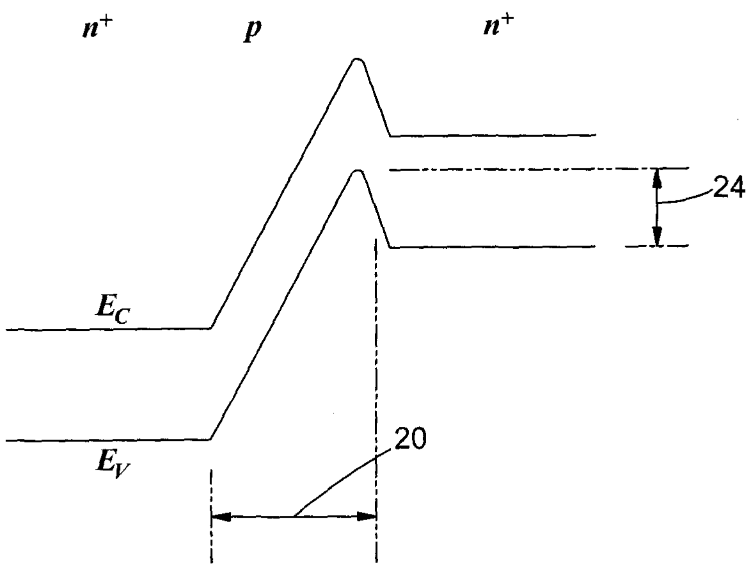

FIGURE 6

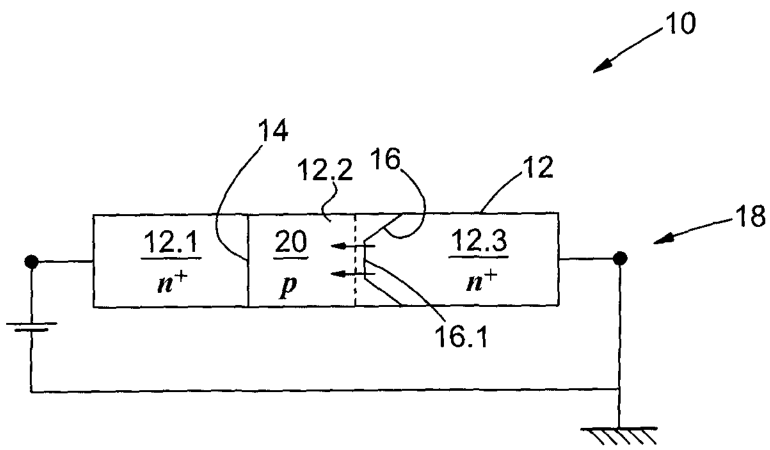

FIGURE 7

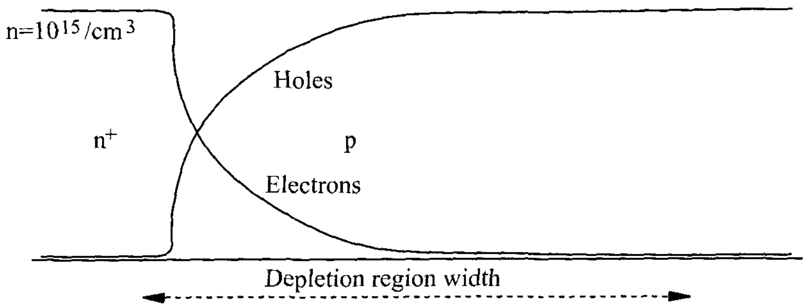

FIGURE 8 (PRIOR ART)

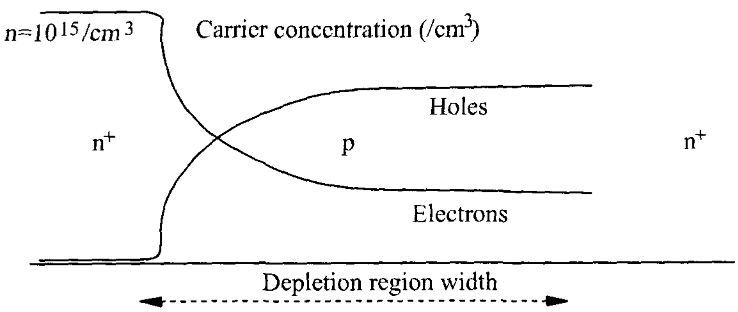

FIGURE 9

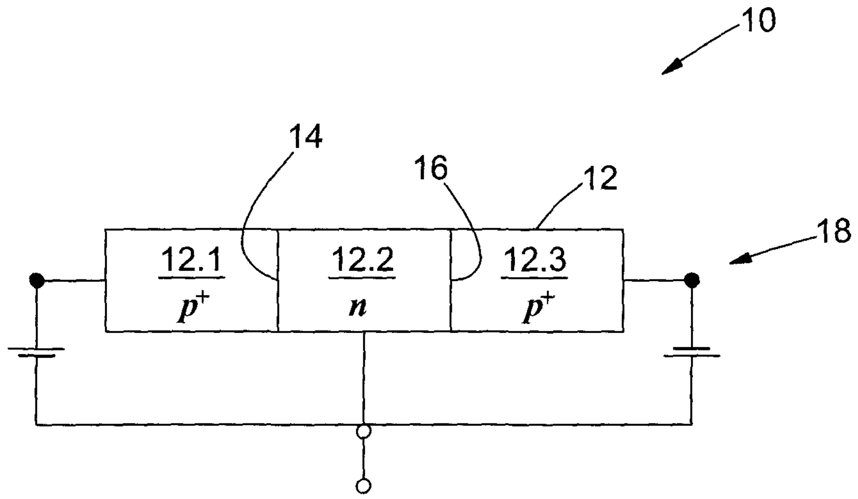

FIGURE 10

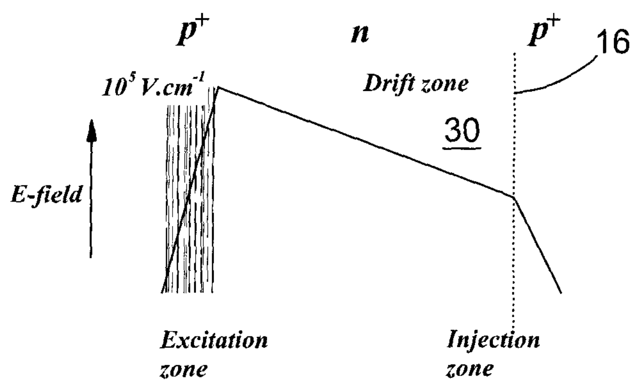

FIGURE 11

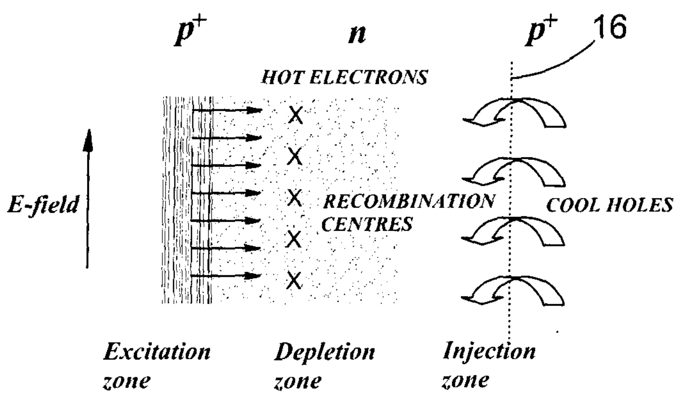

FIGURE 12

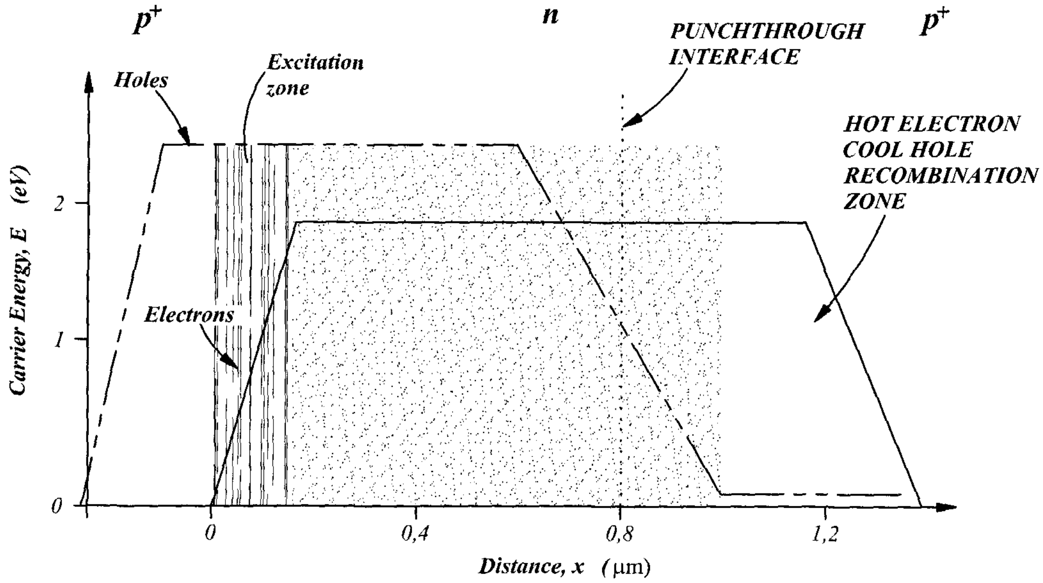

FIGURE 13

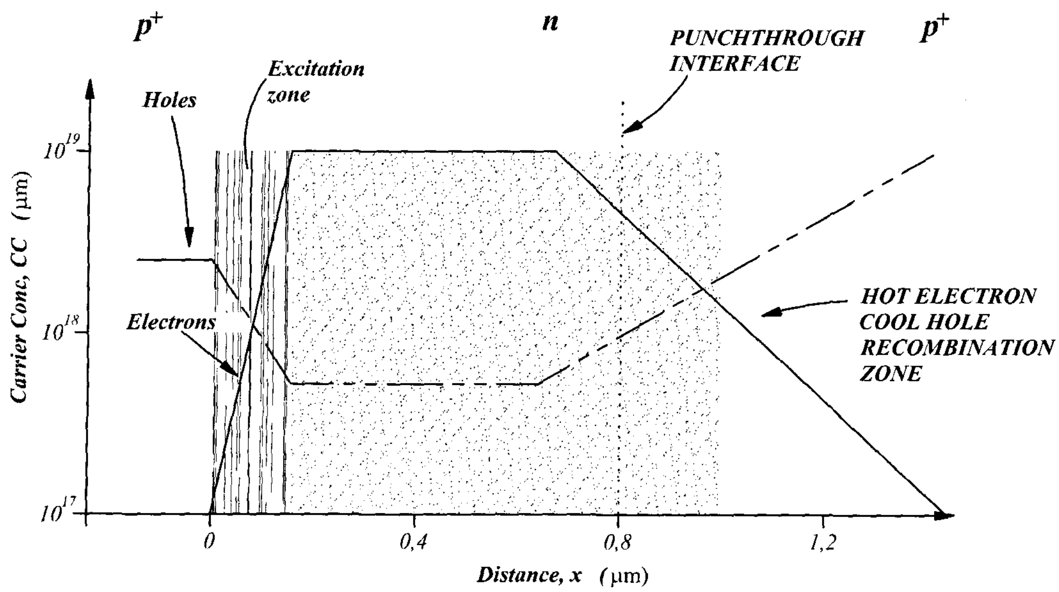

FIGURE 14

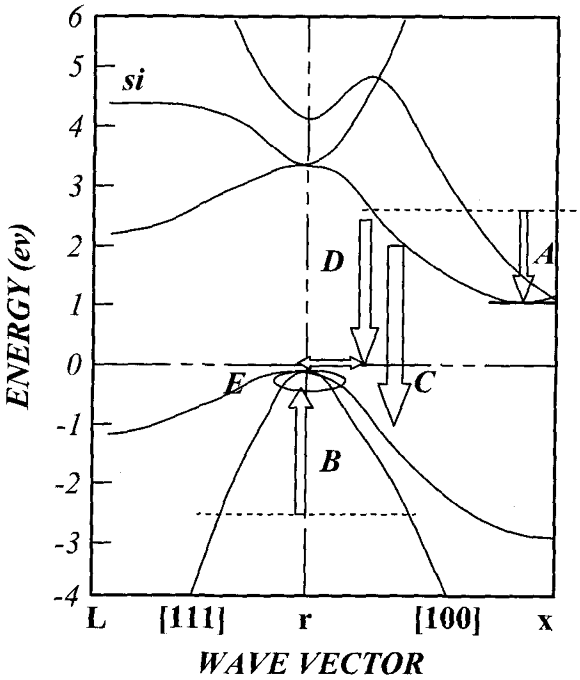

FIGURE 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2009/050209

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L33/34

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 H01S

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 practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SNYMAN L W ET AL: "Injection-avalanche-based n<+>pn silicon complementary metal-oxide-semiconductor light-emitting device (450-750 nm) with 2-order-of-magnitude increase in light emission intensity" JAPANESE JOURNAL OF APPLIED PHYSICS, PART 1 (REGULAR PAPERS, SHORT NOTES & REVIEW PAPERS) JAPAN SOCIETY OF APPLIED PHYSICS THROUGH THE INSTITUTE OF PURE AND APPLIED PHYSICS JAPAN, vol. 46, no. 4B, April 2007 (2007-04), pages 2474-2480, XP002527051 ISSN: 0021-4922 paragraph [0002]; figure 1 -----	1,2, 4-10,12

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

[X] See patent family annex.

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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
8 May 2009	28/05/2009

Name and mailing address of the ISA/	Authorized officer
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International application No
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