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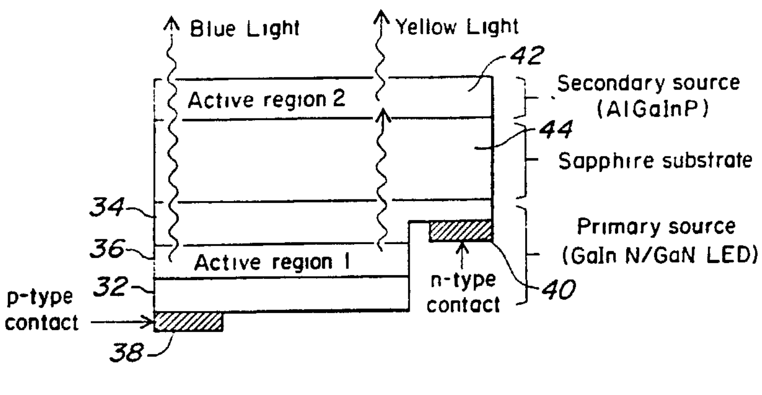
(54) Title: PHOTON RECYCLING SEMICONDUCTOR MULTI-WAVELENGTH LIGHT-EMITTING DIODES



(57) Abstract: A combined light of a white light impression achieved with two semiconductors rather than a semiconductor and a phosphor, dye or polymer converter. There result two substantially monochromatic radiations from the first and second semiconductors or radiation sources. The radiation from two such sources (42, 40) is according to CIE chromaticity diagrams to give the impression of white light.

WO 00/76005 A1

TITLE OF THE INVENTION

PHOTON RECYCLING SEMICONDUCTOR MULTI-WAVELENGTH LIGHT-EMITTING DIODES

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the priority of U.S. Provisional Patent Application No. 60/137,646 filed June 4, 1999 entitled PHOTON RECYCLING SEMICONDUCTOR MULTI-WAVELENGTH LIGHT-EMITTING DIODES

ACKNOWLEDGEMENT OF GOVERNMENT SUPPORT

This invention was made with Government Support under Contract Number ECS 9714047 awarded by the National Science Foundation. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

A source of white light from the combination of two or more substantially monochromatic light sources, as that term is known in the art, is of significant value for use in displays, instruments, and general illumination, particularly where it replaces inefficient incandescent sources

In prior devices using an LED semiconductor primary emitter, a non-semiconductor material such as a phosphor, a dye, or a polymer is provided to respond to light from the LED emitter and convert it into a fairly broad band centered at a longer wavelength than the LED primary emitter light. Together the primary emitter and the wavelength converter materials can create the impression of a nearly white light. Such phosphors increase the cost of a unit. Dyes on the other hand lack long-term stability. Polymers lack sufficient electrical conductivity to carry heavy electrical loads required for high-intensity light outputs.

BRIEF SUMMARY OF THE INVENTION

According to the invention, white light or nearly white light is created with two semiconductor active regions rather than a semiconductor and a phosphor, dye or polymer converter. This results in an emission spectrum consisting of two substantially monochromatic emission bands from the first and second semiconductor active regions or radiation sources. The radiation wavelength from two such sources is selected according to the CIE chromaticity diagrams to give the impression of white light or of another color not located on the perimeter of the chromaticity diagram.

A typical device for providing the light has a first semiconductor formed of doped GaInN (gallium indium nitride) or GaN with a P type confinement region and an N type confinement region and having an active region between the two confinement regions. The active region is stimulated to emit in the blue by an electrical current passing through it. The blue light emits in generally all directions.

A second semiconducting active region is located adjacent to the first semiconductor layers, but can be separated by a sapphire transparent layer upon which the semiconductor layers were initially grown.

The second semiconductor layer can be wafer bonded to the sapphire layer and originally grown on a GaAs substrate that is subsequently removed. The second region is typically AlGaInP (aluminum gallium indium phosphorus) and acts upon the incident light or some of it emitter by the first region in the same way an active P/N junction region responds to the energy in an electrical current to reemit or recycle the light to a longer wavelength.

In an alternative approach, the second active region is also made of GaInN and in that case the two active regions can be grown in one single growth run.

DESCRIPTION OF THE DRAWING

These and other features of the invention are described below in the detailed description in conjunction with the drawing of which:

Fig. 1 is an emission diagram of a prior art device;

Fig. 2 is a chromaticity diagram for phosphor based LED emitters;

Fig. 3 is an emission diagram of a white light emitter of the invention using photon recycling secondary emission;

Fig. 4 is a chromaticity diagram for a photon recycling LED of the invention;

Fig. 5 illustrates the construction go a photon recycling LED for producing white light according to the invention;

Fig. 6 is a diagram of emission wavelength as a function of material composition useful in the present invention;

Fig. 7 is a diagram useful in understanding principles of power ratio in the invention;

Fig. 8 is a diagram illustrating power ratio values as a function of the wavelength of emission from LED light used in photon recycling in practicing the invention;

Fig. 9 illustrates the relationship between material composition and bandgap energy; and

Figs. 10A and 10b illustrate the use of the invention in arrays and large area emitters.

DETAILED DESCRIPTION

The present invention provides a source of white light from the combination of two substantially monochromatic light sources as that term is known in the art by combining the light, typically blue, from a first short wavelength LED source with the light, typically yellow, from secondary emission in a semiconductor material stimulated by incident light of the short wavelength. The use of only two sources reduces the cost compared to prior devices using a combination of the light, for example, from three or more separately activated LEDs.

In other prior devices using a semiconductor primary emitter, a non semiconductor material such as a phosphor, a dye, or a polymer is provided to respond to light from an LED emitter and convert it into a fairly broad band as illustrated in Fig.1 where curve 12 represents that of a blue light LED emitter and curve 14 the emission of a phosphor converter that creates the impression of a nearly white light over the broad emission band plus the LED light. Such phosphors increase the cost of a unit. Dyes on the other hand lack long term stability. Polymers lack sufficient electrical conductivity to carry heavy electrical loads and high intensity light outputs.

A chromaticity diagram such as illustrated in Fig. 2 can be used to understand the principle of achieving white light from a range of light wavelengths such as with phosphors and blue LED sources. The curve 16 starting in the lower left at short or blue wavelengths progresses clockwise with increasing wavelength. The dot 16 at the blue side of the center indicates a perceived light color from the combination of LED and phosphor sources about the curve 16.

According to the invention, a combined light of a white light impression is achieved with two semiconductors rather than a semiconductor and a phosphor, dye or polymer converter. There results two substantially monochromatic radiations, 20 and 22 respectively from the first and second semiconductors or radiation sources. The radiation from two such sources is illustrated in the chromaticity diagram of Fig. 4, with the wavelengths 24 and 26 of the first and second sources combining to give the impression of white light at 28. The chromaticity diagram includes a region 30 about the white resultant at 28 that gives a satisfactory impression of white, depending upon the application.

A typical device for providing the light illustrated in Figs. 3 and 4 is shown in Fig. 5. A first semiconductor is formed of doped GaInN (gallium indium nitride) or GaN with P type region 32 and N type region 34 having a P/N junction 36 or active region which is stimulated to emit in the blue by an electrical current passing through it from respective contacts 38 and 40. The blue light emits in generally all directions but can be directed as desired. A second semiconducting active region 42 is fabricated adjacent to the first semiconductor layers 32-34, but separated by a sapphire transparent layer 44 upon which the layers 32-36 were initially grown according to known fabrication techniques.

The layer 42 is typically wafer bonded to the sapphire layer 44 and originally grown on a GaAs substrate that is subsequently removed by chemically assisted polishing and wet etching. Region 42 is typically AlGaInP (aluminum gallium indium phosphorus). Region 42 acts upon the incident light or some of it from the region 36 through a conductin to valence band transition, such as an active P/N junction region responds to the energy in an electrical current, to reemit or recycle the photons to a longer wavelength.

The wavelengths selected can be any that place the resulting combined radiation into the area 32 of Fig. 4 from sources with wavelengths on opposite sides of the curve 16 and appropriate power levels at each wavelength. Compositions of the material for the primary and secondary emitting semiconductor, such as those noted above, are a function of the elemental concentrations. Fig. 5 is one chart for the combining of AlN, GaN and InN along lines 50, 52 and 54 showing approximate color outputs over a range of concentrations and materials. Other materials and their general wavelength of emissions are illustrated in Fig. 9 below. Preferably, blue emission in a region centered within the range of 420 nm - 480 nm has been found advantageous for the primary emitter and within a color complimentary wavelength in the 500's nm for the secondary emitter. For the primary emitter GaInN as the semiconductor material is useful for this light with silicon doping for N-type confinement regions and magnesium doping for the P-type confinement regions. The yellow region will typically be AlGaInP with concentrations of In varied for the color yellow.

A sapphire substrate as noted above is preferable although other materials such as GaN or SiC are possible. For the semiconducting material other combinations of other elements are also possible such as AlGaAs. Fig. 9 presents the color characteristics of other materials that those skilled in the art could select from. In an alternative approach, the second active region is also made of GaInN and in that case the two active regions can be grown in one single growth run.

Fig. 7 shows diagramatically the division of power between the primary LED emitter 60 and the secondary semiconductor emitter 62. The perception of white light is also a function of the relative power from the two sources, P_1 and P_2. Their ratio, R, is selected to insure whiteness in the output and is based on the relationship shown in Fig 8 where curve 64 gives the power ratio as a function of the wavelength of the primary LED color. The thickness of the layer 42 for the active secondary emitter will vary the power ratio by causing more or less of the photons from the primary LED to be recycled in the active area. For the final chip, the ratio can be adjusted empirically for the desired whiteness.

Large versions or arrays of chips of the type shown in Fig. 5 can be arranged to cause an augmented light output for applications such as panel lights, display lights or ceiling lights, requiring high efficiency white light. Fig. 10A shows a single chip 70 of significant size that can be used for this purpose, while Fig. 10B shows an array 72 of smaller chips 74 assembled to provide an increased intensity of white light output.

The chip of the invention can additionally have plural secondary layers to produce three colors that combine to form white in perception, or some other color.

CLAIMS

IN THE CLAIMS

1. A single chip source of multi-chromatic output light having the visual perception of light inside the periphery of the CIE chromaticity diagram comprising:

a first semiconductor material in said chip responsive to energization to emit light of a first wavelength;

at least one photon recycling second semiconductor material in said chip responsive to radiation of said first wavelength to emit light of a second wavelength longer than the first by photon recycling and along at least said path;

said path having said first wavelength at a first power lever and said second wavelength at a second power;

Said first and second wavelengths and first and second power levels combining to provide output light perception.

2. The source of claim 1 wherein said first and second wavelengths are complementary colors on a CIE chromaticity diagram and said putput light is at least near white.

3. The source of claim 1 where the power ratios of said first and second wavelength emissions satisfy a criteria for said at least near white light.

4. The source of claim 1 wherein said first semiconductor material consists of GaInN.

5. The source of claim 4 wherein said first semiconductor material has an active region formed between P-type and N-type regions thereof.

6. The source of claim 5 wherein said P-type region is doped with magnesium.

7. The source of claim 5 wherein said N-type region is doped with silicon.

8. The source of claim 1 wherein said second semiconductor material is a combination of plural of the elements Al, Ga, In, N, and P, for example AlInGaP or GaInN.

9. The source of claim 1 wherein said first and second semiconductor materials are separated by a transparent material.

10. The source of claim 9 wherein said transparent material is selected from the group consisting of combinations of at least some of Ga, N, Si, and C, for example GaInN or GaN.

11. The source of claim 9 wherein said transparent material includes sapphire.

12. The source of claim 1 wherein said first semiconductor material is a combination of Ga, In, and N.

13. The source of claim 12 wherein said first semiconductor material is adapted for emitting in the range of 20 nm - 480 nm.

14. The source of claim 1 wherein said second semiconductor material is a combination of Al, Ga, In, N and P.

15. The source of claim14 wherein said second semiconducting material is adapted for emitting in a complementary color range to the range of 420 nm - 480 nm.

16. The source of claim 1 further including first and second electrodes contacting said chip to apply electrical current to said first semiconductor material as said energization.

17. The source of claim 5 further including first and second electrodes contacting said P-type and N-type regions for the application of electrical current thereto as said energization.

18. The source of claim 1 further including plural second semiconductor materials.

19. An array of chips of the type of claim 1 providing said at least near white light.

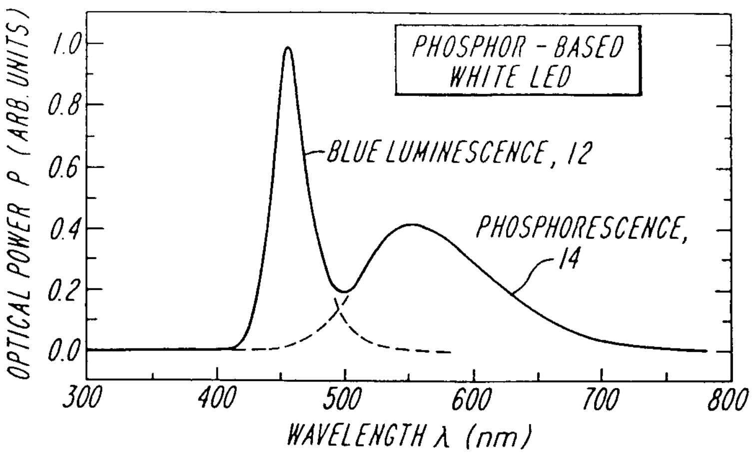


FIG. 1
(PRIOR ART)

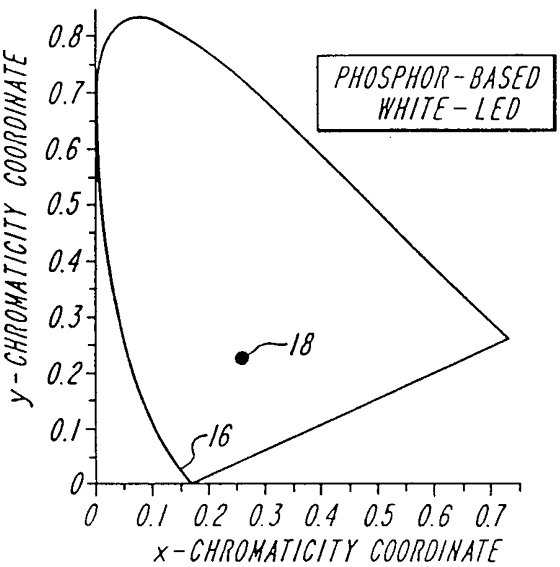


FIG. 2

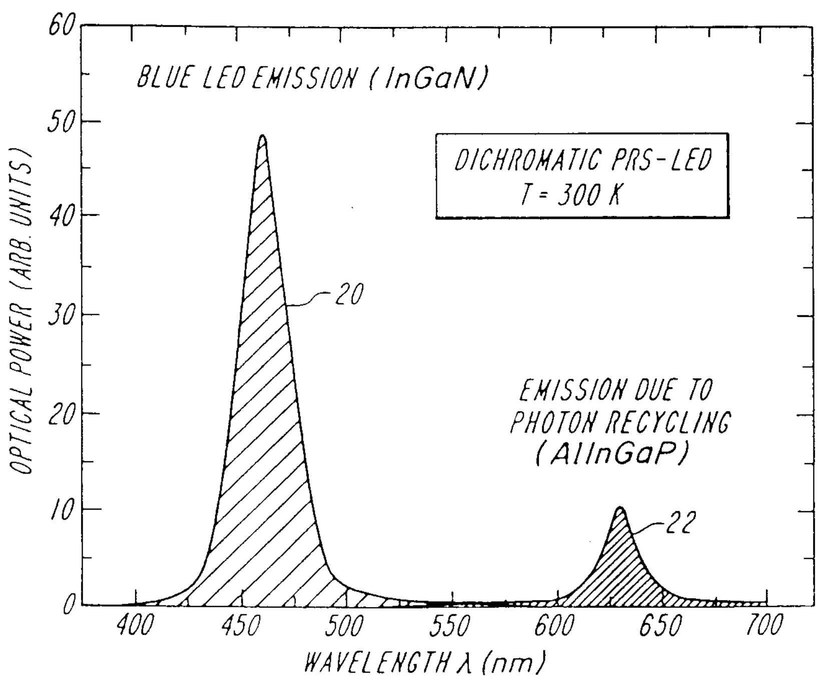
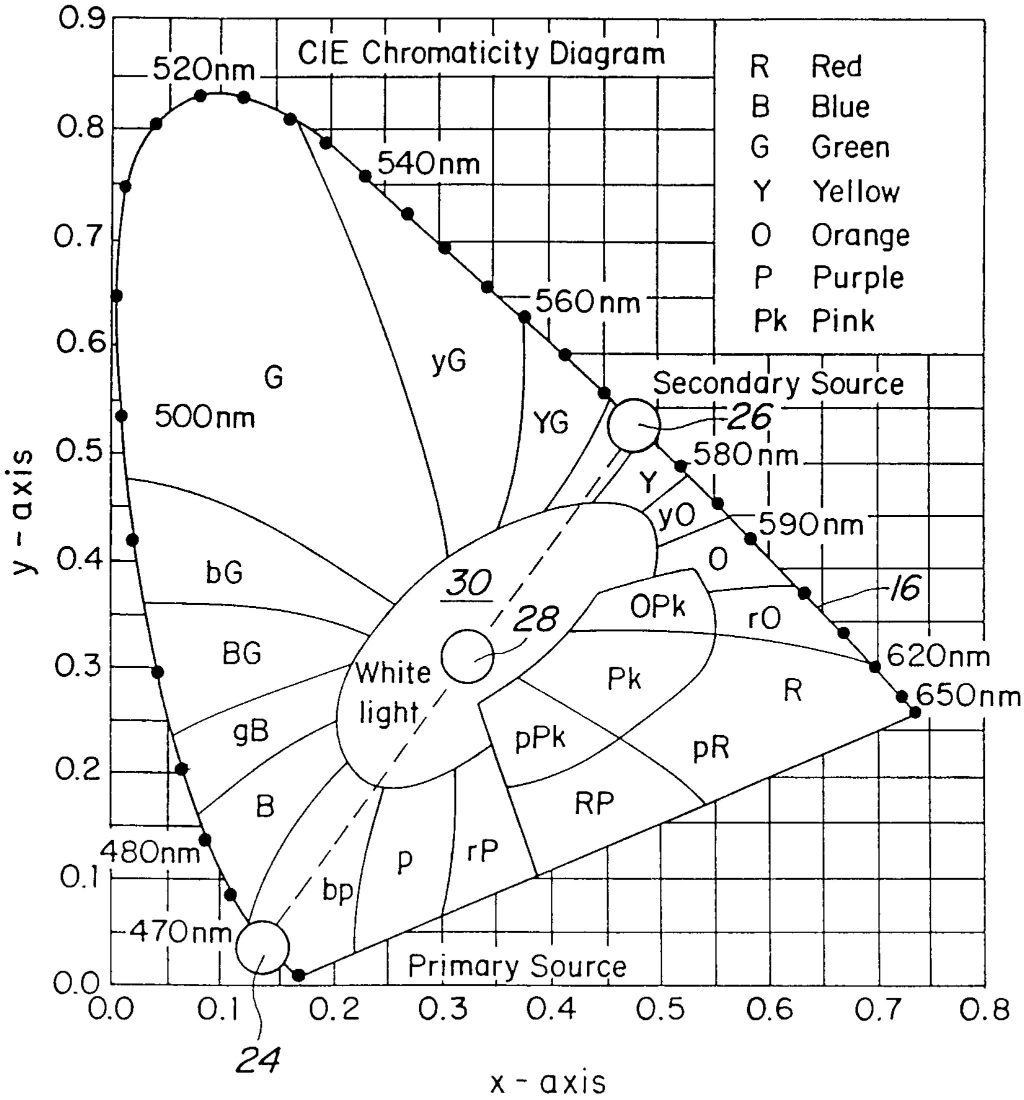


FIG. 3



CIE Chromaticity Diagram
R Red
B Blue
G Green
Y Yellow
O Orange
P Purple
Pk Pink
520nm
540nm
560nm
500nm
580nm
590nm
620nm
650nm
480nm
470nm
G
yG
YG
Y
yO
O
OPk
rO
R
Pk
pPk
pR
RP
rP
p
bp
B
gB
BG
bG
White light
Secondary Source
Primary Source
26
28
30
16
24
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
y - axis
x - axis

FIG. 4

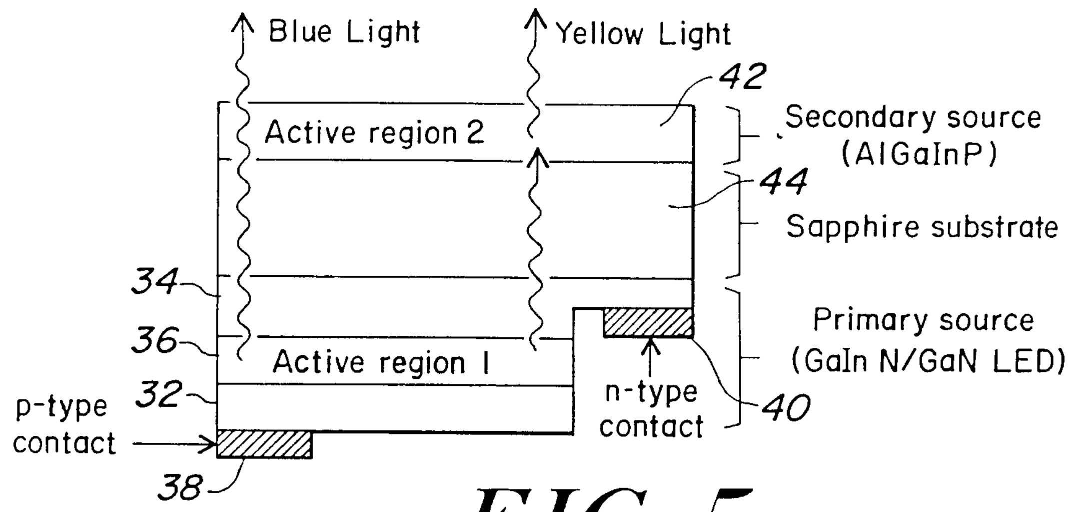

Blue Light
Yellow Light
42
Active region 2
Secondary source
(AlGaInP)
44
Sapphire substrate
34
36
Active region 1
Primary source
(GaIn N/GaN LED)
32
p-type
contact
n-type
contact
40
38

FIG. 5

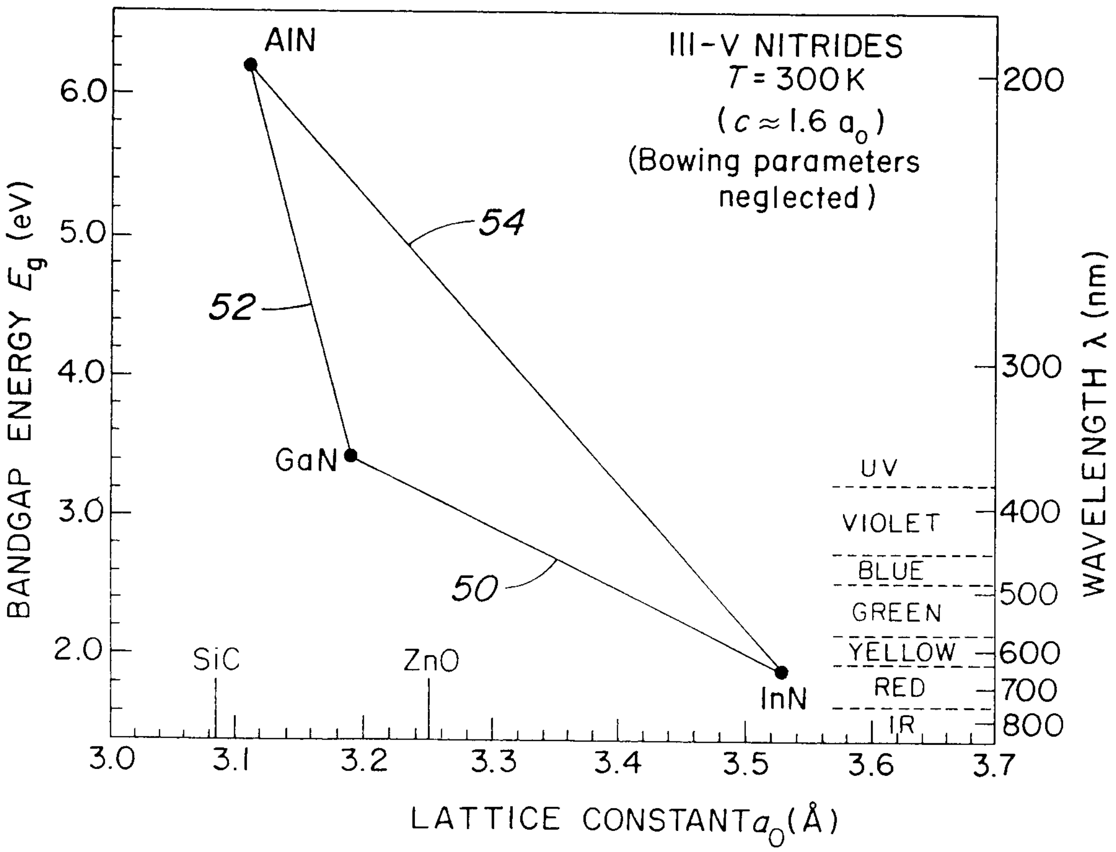

AlN
III-V NITRIDES
T = 300K
(c ≈ 1.6 a0)
(Bowing parameters
neglected)
54
52
GaN
50
InN
SiC
ZnO
UV
VIOLET
BLUE
GREEN
YELLOW
RED
IR
BANDGAP ENERGY Eg (eV)
WAVELENGTH λ (nm)
LATTICE CONSTANT a0 (Å)
6.0
5.0
4.0
3.0
2.0
200
300
400
500
600
700
800
3.0
3.1
3.2
3.3
3.4
3.5
3.6
3.7

FIG. 6

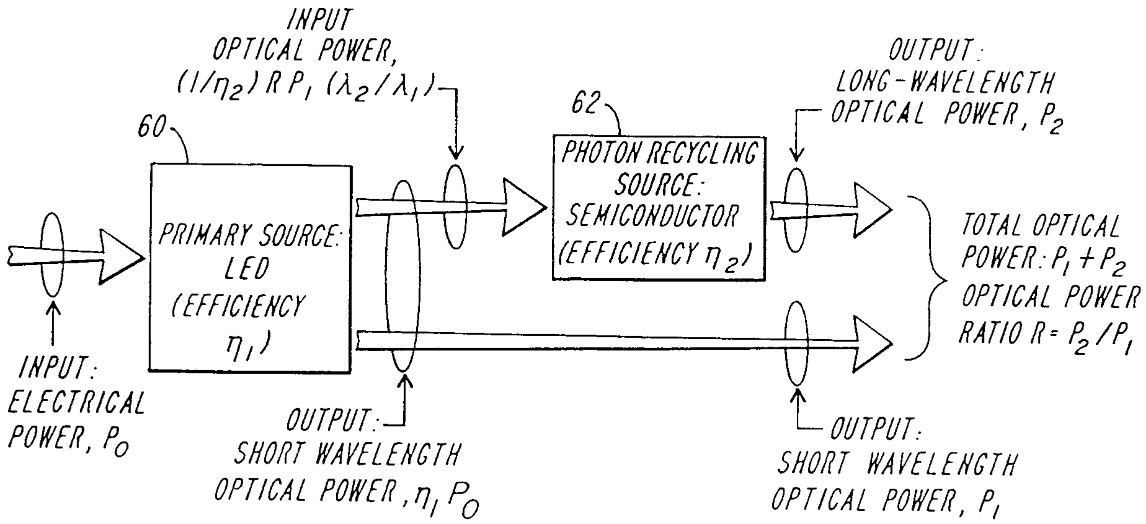

INPUT OPTICAL POWER, (1/η2) R P1 (λ2/λ1)
60
62
PHOTON RECYCLING SOURCE: SEMICONDUCTOR (EFFICIENCY η2)
OUTPUT: LONG-WAVELENGTH OPTICAL POWER, P2
PRIMARY SOURCE: LED (EFFICIENCY η1)
TOTAL OPTICAL POWER: P1 + P2
OPTICAL POWER RATIO R = P2/P1
INPUT: ELECTRICAL POWER, P0
OUTPUT: SHORT WAVELENGTH OPTICAL POWER, η1 P0
OUTPUT: SHORT WAVELENGTH OPTICAL POWER, P1

FIG. 7

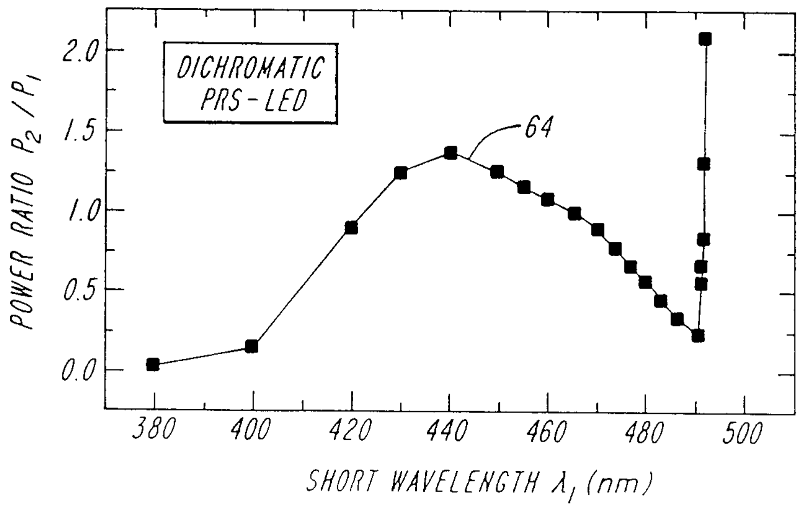

DICHROMATIC PRS-LED
64
POWER RATIO P2 / P1
2.0
1.5
1.0
0.5
0.0
380
400
420
440
460
480
500
SHORT WAVELENGTH λ1 (nm)

FIG. 8

5/6

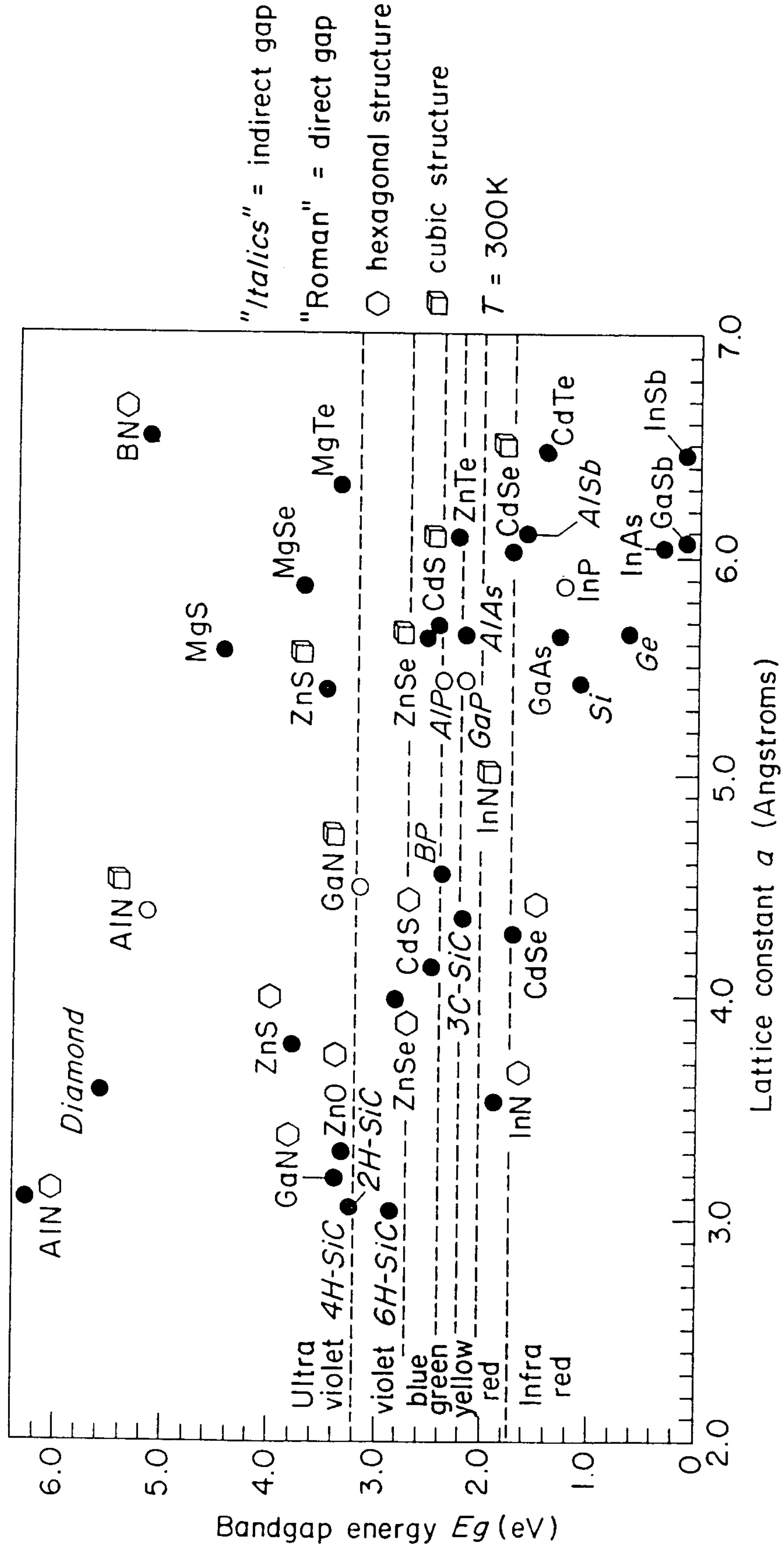

"Italics" = indirect gap
"Roman" = direct gap
hexagonal structure
cubic structure
T = 300K
Bandgap energy Eg (eV)
Lattice constant a (Angstroms)
Ultra violet
violet
blue
green
yellow
red
Infra red
4H-SiC
6H-SiC
2H-SiC
AlN
GaN
ZnO
Diamond
ZnS
ZnSe
CdS
CdSe
InN
3C-SiC
BP
AlP
GaP
AlAs
MgS
MgSe
MgTe
ZnTe
CdTe
AlSb
Si
GaAs
Ge
InP
InAs
GaSb
InSb
BN

FIG. 9

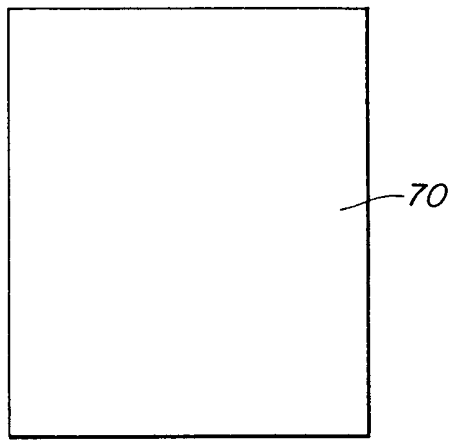


FIG. 10A

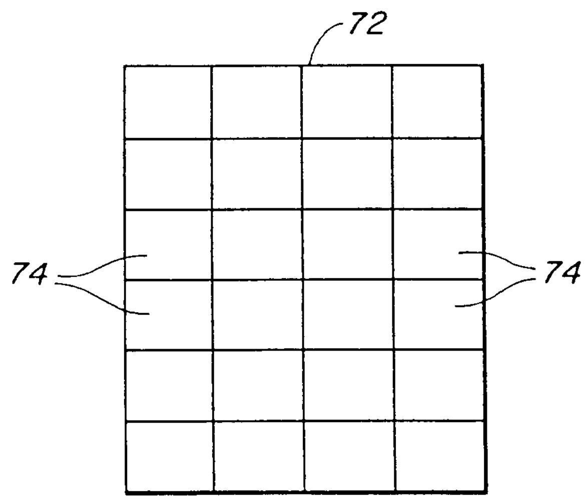


FIG. 10B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/15412

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01L 33/00
US CL : 257/98
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. : 257/98, 80, 81, 82, 85 89

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)

EAST
search terms: LED, light emitting diode, photoluminescent, color converter, III-N, nitride, nitrogen, GaN, blue, white

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,898,185 A (BOJARCZUK, JR. et al) 27 April 1999, (27/04/99) FIGs. 1 and 7A.	1, 4-7, 9, 11-13, 16-19
X,P ---- Y,P	US 5,966,393 a (Hide et al) 12 October 1999, (12/10/99) col. 5-9; col. 13, lines 55-67; col. 14, lines 36-.	1-5, 9, 11-13, 16-18 ---- 6, 7, 10, 19
X ---- Y	US 5,813,752 A (Singer et al) 29 September 1998, (29/09/98) cols. 1-5.	1-5, 9, 10, 12, 13, 16-19 ---- 6, 7
A	US 5,739,552 A (Kimura et al) 14 April 1998, (14/04/98) all.	1-19

[X] 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 document 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	Date of mailing of the international search report
27 JULY 2000	21 AUG 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	B. WILLIAM BAUMEISTER
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0956

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/15412

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US 5,952,681 A (Chen) 14 September 1999, (14/09/99) all	1-19