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(12) **United States Patent**
Gunapala et al.

(10) **Patent No.: US 6,271,537 B1**
(45) **Date of Patent: Aug. 7, 2001**

(54) **SLOTTED QUANTUM WELL SENSOR**

(75) Inventors: **Sarath D. Gunapala**; **Sumith V. Bandara**, both of Valencia; **John K. Liu**, Pasadena; **Daniel W. Wilson**, Montrose, all of CA (US)

(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/443,177**

(22) Filed: **Nov. 19, 1999**

Related U.S. Application Data

(60) Provisional application No. 60/109,329, filed on Nov. 20, 1998.

(51) **Int. Cl.**[7] **H01L 31/0352**; H01L 31/05; H01L 31/101; H01L 21/764

(52) **U.S. Cl.** **257/21**; 257/184; 257/189; 257/436; 257/446; 257/447; 257/448; 438/71; 438/73; 250/338.4; 250/339.02

(58) **Field of Search** 257/21, 184, 189, 257/436, 447, 448, 446; 438/71, 73; 250/338.4, 339.01, 339.02

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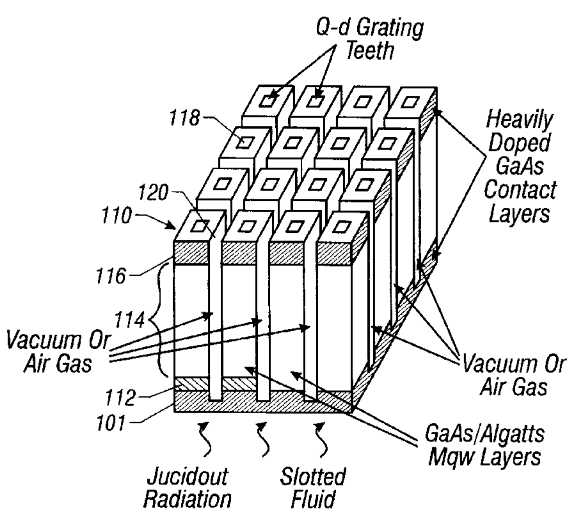
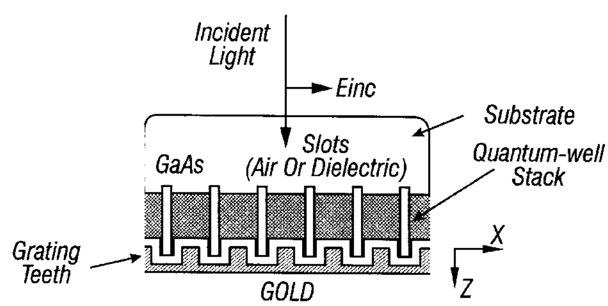
Primary Examiner—Eddie Lee
Assistant Examiner—Bradley W. Baumeister
(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

Quantum-well sensors having an array of spatially separated quantum-well columns formed on a substrate. A grating can be formed increase the coupling efficiency.

13 Claims, 2 Drawing Sheets





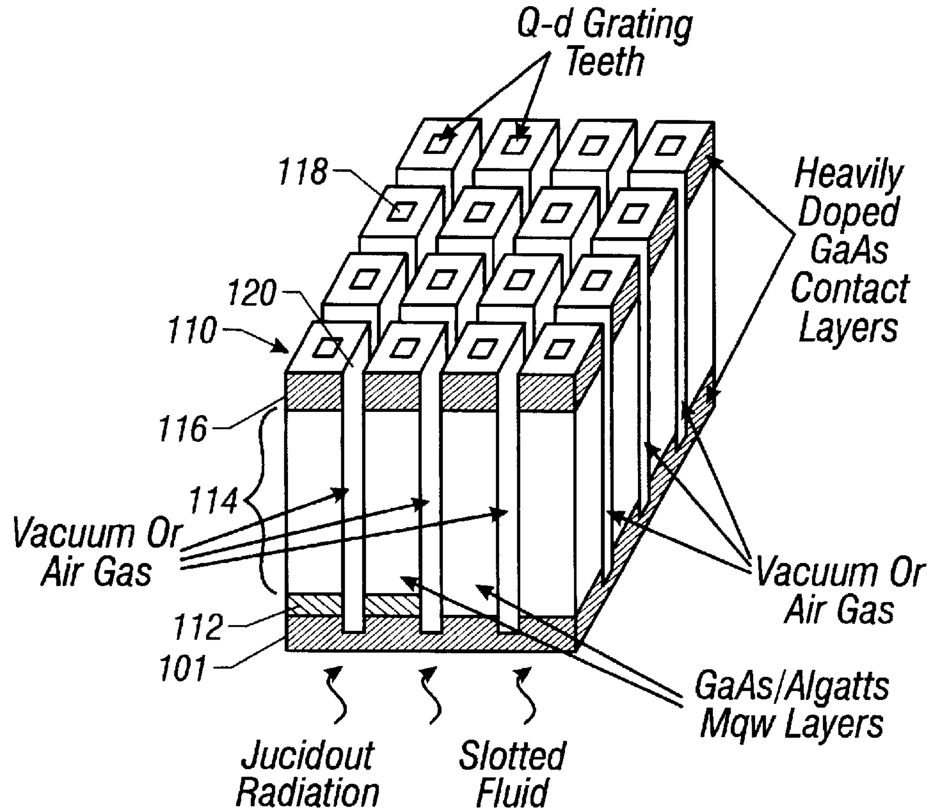

Q-d Grating
Teeth
118
120
110
116
114
112
101
Heavily
Doped
GaAs
Contact
Layers
Vacuum Or
Air Gas
Vacuum Or
Air Gas
GaAs/Algatts
Mqw Layers
Jucidout
Radiation
Slotted
Fluid

FIG. 1

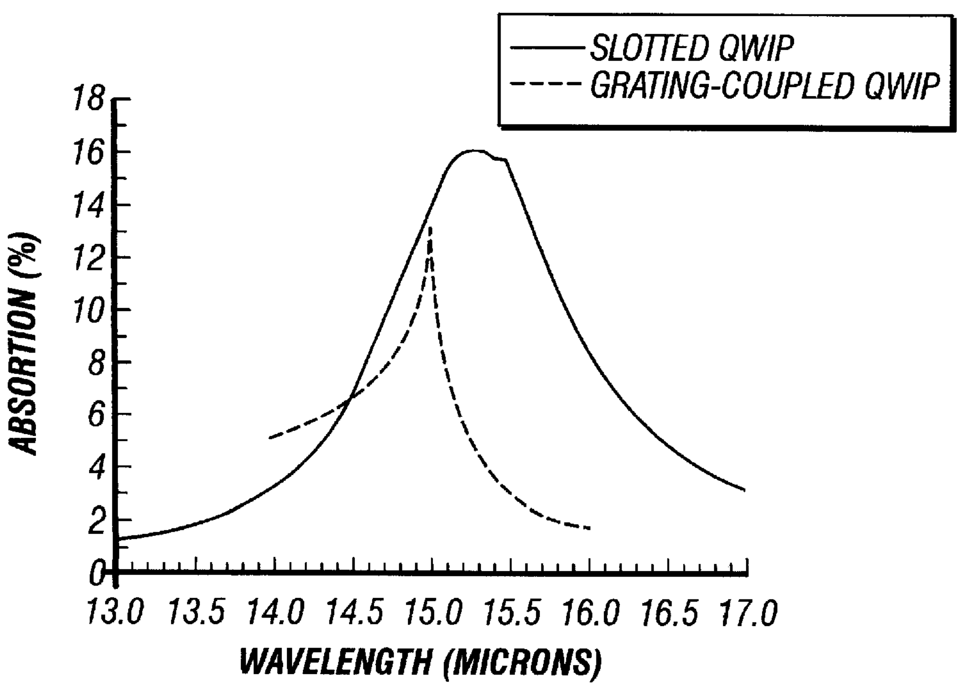

SLOTTED QWIP
GRATING-COUPLED QWIP
ABSORPTION (%)
0
2
4
6
8
10
12
14
16
18
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
17.0
WAVELENGTH (MICRONS)

FIG. 2

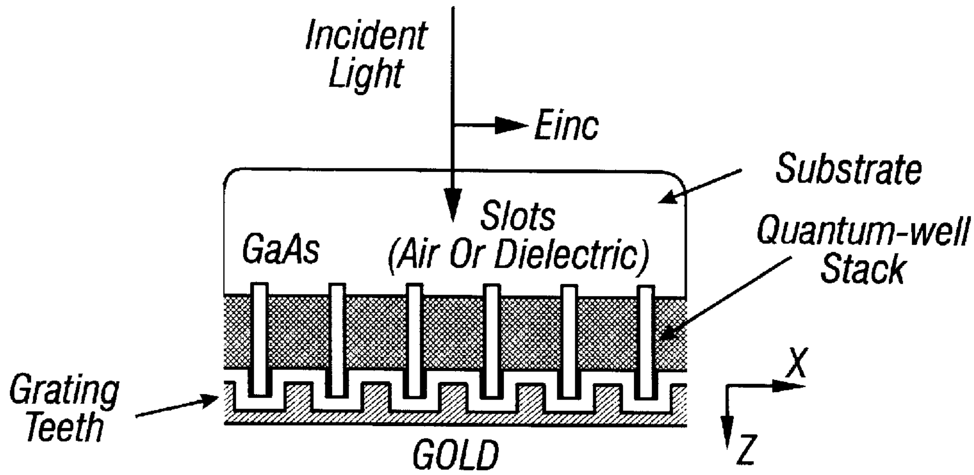


FIG. 3

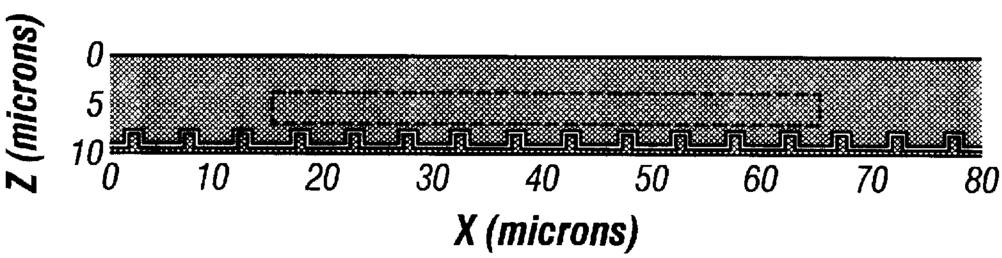


FIG. 4

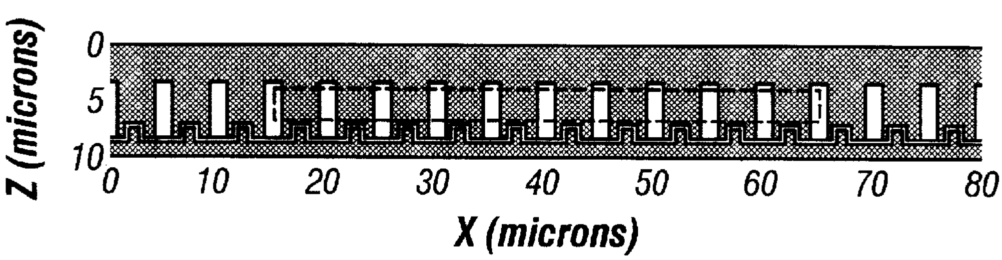


FIG. 5

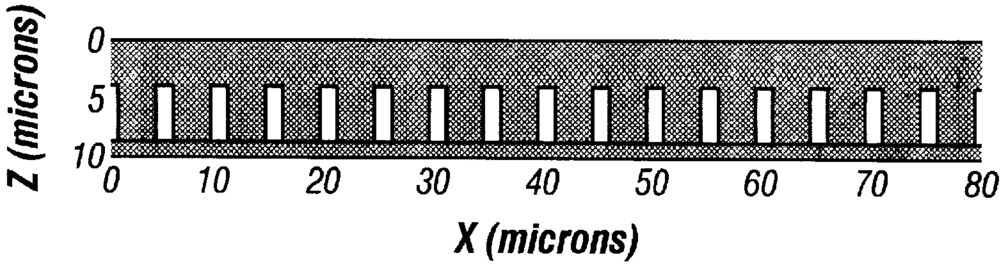


FIG. 6

SLOTTED QUANTUM WELL SENSOR

This application claims the benefit of U.S. Provisional Application No. 60/109,329, filed on Nov. 20, 1998.

ORIGIN

The devices and techniques described herein were made in the performance of work under a NASA contract, and are subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the Contractor has elected to retain title.

BACKGROUND

This specification relates to quantum-well radiation sensors and techniques of constructing quantum-well radiation sensors with reduced noise.

An infrared quantum-well semiconductor sensor includes a quantum-well structure formed of alternating active and barrier semiconductor layers. Such a quantum-well structure can have different energy bands which each can have multiple quantum states. An intraband transition between a ground state and an excited state in the same band (i.e., a conduction band or a valance band) can be used to detect infrared ("IR") radiation by absorbing IR radiation at or near a selected resonance IR wavelength. Only incident radiation with a polarization that is perpendicular to the quantum well layers can be absorbed, because this polarization can induce an intraband transition. The absorption of the radiation generates electric charge indicative of the amount of received radiation. The radiation-induced charge can then be converted into an electrical signal (e.g., a voltage or current) to be processed by signal processing circuitry.

The total charge produced by an IR quantum-well sensor generally includes two major contributions. One is radiation-induced charge which indicates the amount of radiation being absorbed by the quantum-well layers. Another contribution is the charge that is not produced by absorption of radiation. Rather, such non-radiation-induced charge is caused by thermal effects, quantum tunneling effect, shot noise, and other fluctuation processes. The motion of certain non-radiation-induced charge under a bias electrical field generates an electrical current called the dark current. This dark current is undesirable since it does not reflect the amount of radiation to be detected. In addition, it can saturate the detection circuitry and hence adversely affect the detection of the radiation-induced signal.

SUMMARY

The present devices and techniques use an array of quantum-well columns of either one dimension or two dimensions formed on a substrate to couple incident radiation to have a polarization perpendicular to the quantum-well layers for intraband absorption and to reduce the dark current.

In one embodiment, a quantum-well semiconductor device includes a plurality of quantum-well columns spatially separated from one another by a gap which is electrically insulating and formed over a substrate to form a periodic array. Each quantum-well column includes, a first conductive contact layer formed over the substrate, a quantum-well stack having a plurality of alternating quantum-well layers parallel formed over the first conductive contact layer and operating to absorb radiation polarized perpendicularly to the quantum-well layers, and a second conductive contact layer formed over the quantum-well stack.

These and other features and associated advantages of the devices and techniques are described in detail in the following.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows on embodiment of a 2-dimensional slotted quantum-well sensor having quantum-well columns separated by low-index insulating gaps.

FIG. **2** shows calculated absorption spectra of a slotted quantum-well sensor and a conventional grating-coupled quantum-well sensor without slots. The calculation is based on a coupled wave analysis by using the same level of anisotropic absorption: $n_x=3.1$, $n_z=3.1-j\ (\alpha_z\lambda/4\pi)$, $\alpha_z=84\ cm^{-1}$.

FIG. **3** shows a structure of a 1-dimensional array of quantum-well columns having grating teeth.

FIG. **4** shows the calculated magnitude of the coupled radiation with its electric field (E_z) perpendicular to the quantum-well layers for a grating-coupled quantum-well sensor similarly constructed as in FIG. **2** but without slots.

FIGS. **5** and **6** respectively show the calculated electric field (E_z) in the quantum-well layers for sensors with and without the grating teeth.

DETAILED DESCRIPTION

An intraband quantum-well sensor can be formed of an array of columnar shaped quantum-wells on a substrate. The columns can be arranged in a one dimensional array or in a two dimensional array. The columnar elements can be square, rectangular, round, elliptical or irregular in cross section each can be similarly shaped or they can be different. FIG. **1** shows one embodiment of such a "slotted" sensor **100** having a two-dimensional array of quantum-well columns **110** on a substrate **102**. Any two adjacent quantum-well columns **110** are completely separated by a gap **120**. Each quantum-well column **110** includes a first conductive contact layer **112** which is directly formed over the substrate **102**, a quantum-well stack **114** of multiple alternating semiconductor layers (active and barrier layers) to absorb radiation at one or more wavelengths. The quantum-well layers are parallel to the surface of the substrate **102** and may include two or more stacks of different quantum well structures that have intraband transitions at different wavelengths to allow each column **110** to detect radiation of different colors. One or more columns **110** may be grouped together to form a single sensing pixel of a sensor array.

A second conductive contact layer **116** is directly formed over the quantum-well stack **114** so that the quantum-well stack **114** is sandwiched between the contact layers **112** and **116**. Different electrical potentials are applied to the layers **112** and **116** to properly bias the quantum-well stack **114**. Heavily-doped semiconductor materials (e.g., GaAs) may be used as the contact layers **112** and **116**.

The gap **120** between adjacent columns **110** is formed by removing quantum-well layers and other layers above the substrate **102** by, e.g., etching. The gap **120** may be etched slightly into the substrate **102** to ensure complete separation between any two adjacent columns **110**. The gap **120** is electrically insulating and may be evacuated or filled with air, or an insulating material. The index of refraction of the gap **120** is less than that of each quantum-well column **110**. Hence, each column **110** is an independent sensor which is electrically isolated from other columns.

Different columns **110**, however, are not completely separated in their optical properties. The array of the columns

110 is a periodic structure and hence can be collectively used to construct a two-dimensional optical grating. This grating can be used to couple a portion of the incident radiation into each quantum-well column 110 with a polarization perpendicular to the quantum-well layers. It has been discovered that the coupling efficiency of this grating can be increased by forming a metallic grating tooth 118 on top of each quantum-well column 110. The grating tooth 118 may be a square layer formed of gold, for example.

In addition, this array of columns 110 is optically different from a conventional diffraction grating. Its bandwidth is broader, to allow detection of different wavelengths within its bandwidth. FIG. 2 compares the absorption bandwidths of a grating-coupled quantum-well sensor without slots and a slotted quantum-well sensor.

Each quantum-well column 110 also functions as an optical cavity with its side walls forming its reflective surfaces. Since the refractive index of the quantum-well column 110 is selected to be greater than that of the gap 120, certain rays entering the column 110 from the substrate 102 may undergo one or more total internal reflections. In this sense, each quantum-well column 110 is also a waveguide. Hence, the actual interaction length is increased. The absorption by the quantum-well layers is correspondingly increased. This further increases the coupling efficiency of the device 100. Certain parameters of each column 110, including column width, gap width, and gap index, are adjusted to achieve a resonance condition of the optical cavity, to increase the magnitude of the electric field perpendicular to the quantum-well layers and therefore the coupling efficiency. Measurements also indicate that these quantum-well columns 110 exhibit weak optical coupling to a certain extent.

Another feature of the slotted quantum-well sensor 100 is its reduced dark current. The dark current is approximately proportional to the dimension of the cross section (i.e., the square root of the area) of the quantum-well region in a quantum-well sensor. The presence of the gap 120 between adjacent quantum-well columns 110 reduces the cross-sectional area of the quantum-well layers and hence the dark current as compared to a sensor without the gap 120.

FIG. 3 shows a structure of a 1-dimensional array of quantum-well columns. FIG. 4 shows the calculated magnitude of the coupled radiation with its electric field (E_z) perpendicular to the quantum-well layers for a grating-coupled quantum-well sensor similarly constructed as in FIG. 2 but without slots. As a comparison, FIGS. 5 and 6 respectively show the calculated electric field (E_z) in the quantum-well layers for sensors with and without the grating teeth. The calculations are performed by solving a finite-difference Helmholtz equation. The calculation results suggest that the coupling efficiency of the slotted sensor shown in FIG. 5 is triple the coupling efficiency of a non-slotted sensor shown in FIG. 4 even after about 30% of the quantum-well material is removed. In addition, the presence of the grating teeth in the slotted sensor plays a significant role in achieving the excellent coupling efficiency.

Although only a few embodiments are disclosed, other embodiments, variations, and modifications are to be encompassed by the following claims.

What is claimed is:

1. A quantum-well semiconductor device that senses radiation energy, comprising:

a substrate of a substantially transparent semiconductor material to receive the radiation energy;

a plurality of quantum-well structures formed over said substrate, arranged in columnar shapes and spatially separated from one another by a gap to form an optical grating that diffracts the radiation energy said gap being electrically insulating, and

a plurality of separate metallic elements respectively formed over said quantum-well structures to enhance a diffraction efficiency of said optical grating,

wherein each quantum-well structure includes, a first conductive contact layer formed over said substrate, a quantum-well stack having a plurality of alternating quantum-well layers formed in parallel over said first conductive contact layer and operating to absorb radiation polarized perpendicularly to said quantum-well layers, and a second conductive contact layer formed over said quantum-well stack, and

wherein said gap between two adjacent quantum-well structures is configured to spatially separate and electrically insulate each layer of one quantum-well structure from each layer of another quantum-well structure.

2. A device as in claim 1, wherein each metallic element includes a metallic piece formed over said second conductive contact layer.

3. A device as in claim 1, wherein dimensions and indices of said plurality of quantum-well structures and said gap are configured to make each quantum-well structure an optical cavity in a resonance condition so that a magnitude of received radiation having a polarization perpendicular to said quantum-well layers is greater than a magnitude of received radiation having a polarization perpendicular to said quantum-well layers when the resonance condition is not met.

4. A device as in claim 1, wherein said gap between adjacent quantum-well structures has an index of refraction less than an index of refraction of each quantum-well structure.

5. A device as in claim 1, wherein each quantum-well structure includes at least two different stacks of quantum-well layers, each stack configured to have a different intraband transition.

6. A quantum-well semiconductor device that senses radiation energy, comprising:

a substrate of a substantially transparent semiconductor material; and

a plurality of quantum-well columns spatially separated from one another by an electrically-insulating gap and formed over said substrate to form a periodic array that diffracts the radiation energy,

wherein each quantum-well column includes, a first conductive contact layer formed over said substrate, a quantum-well stack having a plurality of alternating quantum-well layers parallel formed over said first conductive contact layer and operating to absorb radiation by at least one intraband transition, and a second conductive contact layer formed over said quantum-well stack, and said gap between two adjacent quantum-well columns is configured to spatially separate and electrically insulate each layer of one quantum-well column from each layer of another quantum-well column, and

wherein dimensions and indices of said plurality of quantum-well columns and said gap are configured to make each quantum-well column an optical cavity in a resonance condition so that a magnitude of received radiation having a polarization perpendicular to said quantum-well layers is greater than a magnitude of received radiation having a polarization perpendicular to said quantum-well layers when the resonance condition is not met.

7. A device as in claim **6**, further comprising a grating which includes a plurality of identical grating teeth respectively formed over said second contact layer in said plurality of quantum-well columns.

8. A device as in claim **6**, wherein each of said first and second contact layers is formed of a doped semiconductor.

9. A device as in claim **6**, wherein said gap between adjacent quantum-well columns has an index of refraction less than an index of refraction of each quantum-well column.

10. A device as in claim **6**, wherein each quantum-well column includes at least two different stacks of quantum-well layers, each stack configured to have a different intraband transition.

11. A method for detecting radiation by using a quantum-well structure that absorbs radiation by an intraband transition, comprising:

providing a plurality of quantum-well columns spatially separated from one another by an electrically-insulating gap and formed over a transparent substrate to form a periodic array, wherein each quantum-well column includes a plurality of alternating quantum-well layers formed between two opposing conductive contact layers;

configuring said gap between two adjacent quantum-well columns to spatially separate and electrically insulate each layer of one quantum-well column from each layer of another quantum-well column;

configuring dimensions of said quantum-well columns and said gap to form an optical grating and to diffract the radiation energy;

placing a plurality of identical, separate grating teeth respectively on said quantum-well columns to enhance a diffraction efficiency of said optical grating; and

directing an incident radiation beam into each quantum-well column through the substrate to produce radiation polarization perpendicular to said quantum-well layers.

12. A method as in claim **11**, further comprising selecting the dimensions and indices of the plurality of quantum-well columns and the electrically-insulating gap to make each quantum-well column an optical cavity in a resonance condition so that a magnitude of received radiation having a polarization perpendicular to said quantum-well layers is higher than a magnitude of received radiation having a polarization perpendicular to said quantum-well layers when the resonance condition is not met.

13. A method as in claim **11**, wherein the electrically insulating gap includes a dielectric insulator that has an index of refraction less than an index of refraction of each quantum-well column.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,271,537 B1
DATED : August 7, 2001
INVENTOR(S) : Gunapala et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

The title page showing an illustrated figure, should be deleted and substituted therefor the attached title page.

Delete drawing sheet 1, and substitute therefor the attached drawing sheet.

Signed and Sealed this

Eighth Day of July, 2003

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

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Primary Examiner—Eddie Lee
Assistant Examiner—Bradley W. Baumeister
(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

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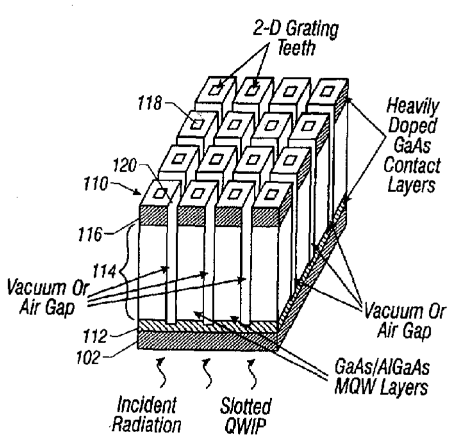

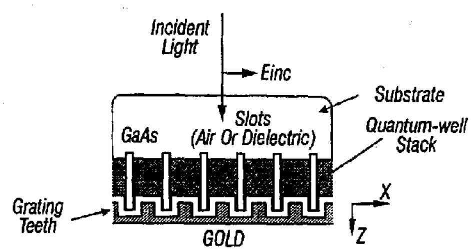

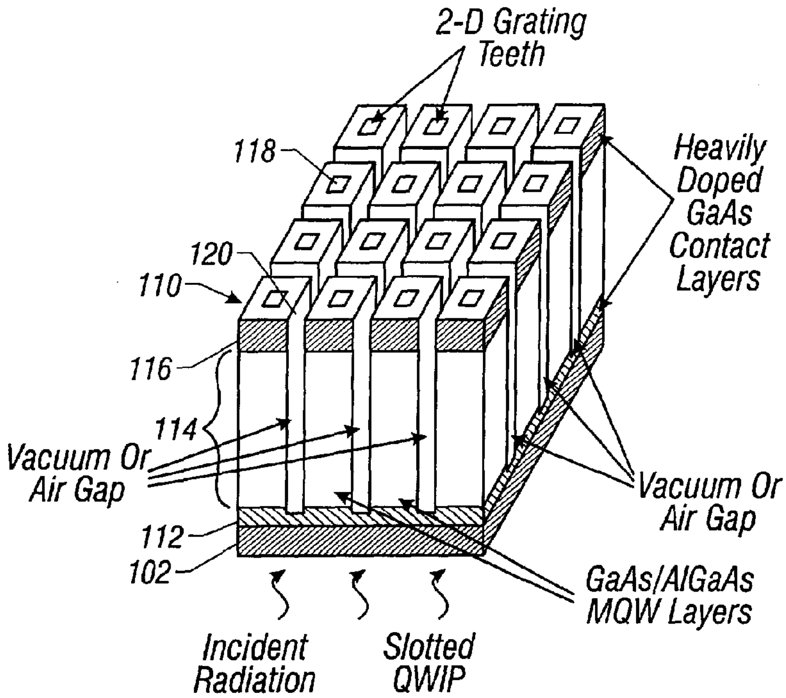
2-D Grating Teeth
118
120
110
116
114
Vacuum Or Air Gap
112
102
Heavily Doped GaAs Contact Layers
Vacuum Or Air Gap
GaAs/AlGaAs MQW Layers
Incident Radiation
Slotted QWIP

FIG. 1

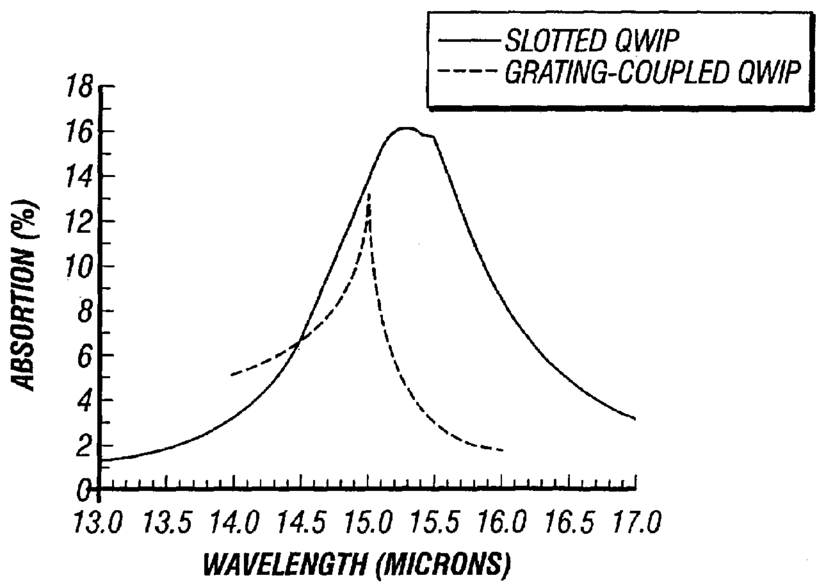
SLOTTED QWIP
GRATING-COUPLED QWIP
ABSORPTION (%)
18
16
14
12
10
8
6
4
2
0
13.0 13.5 14.0 14.5 15.0 15.5 16.0 16.5 17.0
WAVELENGTH (MICRONS)

FIG. 2