United States Patent [19]

Miller

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[45] **Reissued Date of Patent: Mar. 21, 1989**

[54] **NONLINEAR AND BISTABLE OPTICAL DEVICE**

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[73] Assignee: **American Telephone and Telegraph Company, AT&T Bell Laboratories**, Murray Hill, N.J.

[21] Appl. No.: **105,770**

[22] Filed: **Oct. 6, 1987**

Related U.S. Patent Documents

Reissue of:

[64] Patent No.: **4,546,244**
Issued: **Oct. 8, 1985**
Appl. No.: **589,556**
Filed: **Mar. 14, 1984**

[51] **Int. Cl.**[4] **H01J 40/14**

[52] **U.S. Cl.** ..... **250/211 J**; 377/102; 372/12; 372/45; 372/46; 357/30

[58] **Field of Search** ..... 250/211 J; 340/870.29; 377/102; 372/12, 45, 46; 350/354; 357/30

[56] **References Cited**

PUBLICATIONS

T. A. Wood, et al., "High-Speed Optical Modulation with GaAs/GaAlAs Quantum Wells in a p-i-n Diode Structure", Appl Phys. Lett. 43(1), Jan. 1, 1984, pp. 16-18.

K. Bohnert et al., "Intrinsic Absorptive Optical Bistability in CdS", App. Phys. Lett. (43(12), Dec. 15, 1983, pp. 1088-1090.

Hajto et al., "Optical Bistability Observed in Amorphous Semiconductor Films", Philos. Mag. B, 1983, 47, #4, pp. 347-366.

Primary Examiner—J. David Welsh
Attorney, Agent, or Firm—Gregory C. Ranieri

[57] **ABSTRACT**

The invention is a nonlinear or bistable optical device having a low switching energy. The invention uses a means responsive to light for generating a photocurrent, a structure having a semiconductor quantum well region, and means responsive to the photocurrent for electrically controlling an optical absorption of the semiconductor quantum well region. The optical absorption of the semiconductor quantum well region varies in response to variations in the photocurrent. A photodiode or phototransistor may be used as the means responsive to light, and may be made integral with the structure having the semiconductor quantum well region. An array of devices may be fabricated on a single chip for parallel logic processing.

52 Claims, 13 Drawing Sheets

FIG. 1

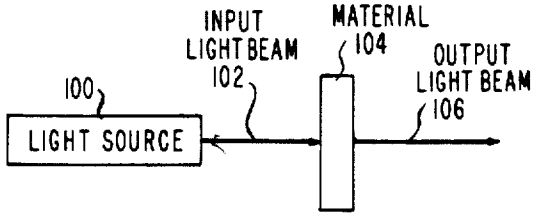


FIG. 2

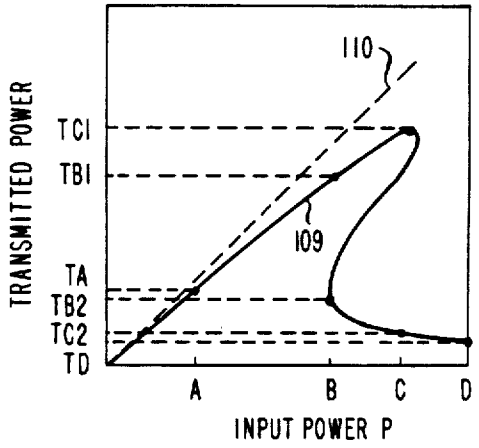


FIG. 3

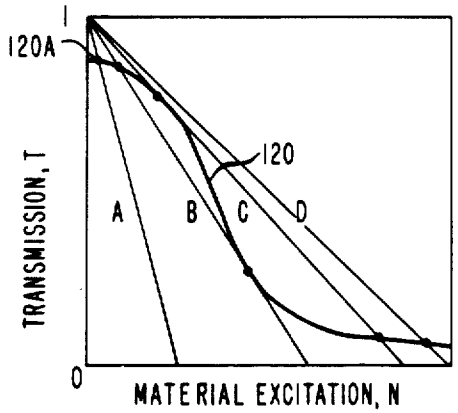


FIG. 4

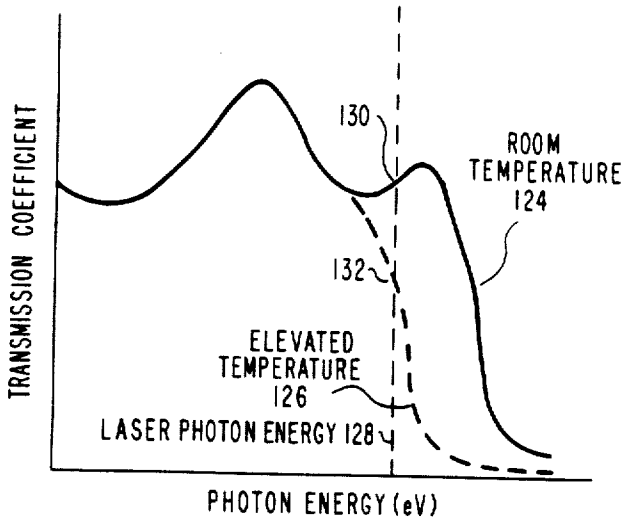

TRANSMISSION COEFFICIENT
130
ROOM TEMPERATURE 124
132
ELEVATED TEMPERATURE 126
LASER PHOTON ENERGY 128
PHOTON ENERGY (eV)

FIG. 5

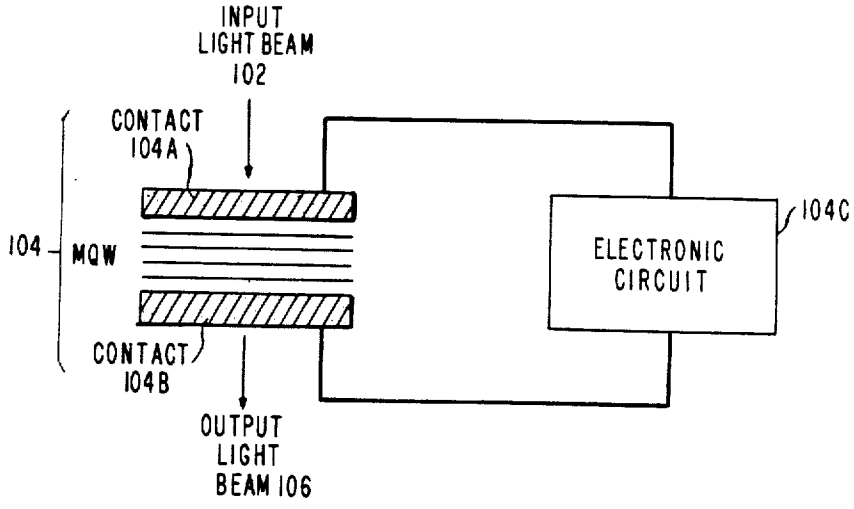

INPUT LIGHT BEAM 102
CONTACT 104A
104
MQW
CONTACT 104B
OUTPUT LIGHT BEAM 106
ELECTRONIC CIRCUIT
104C

FIG. 6

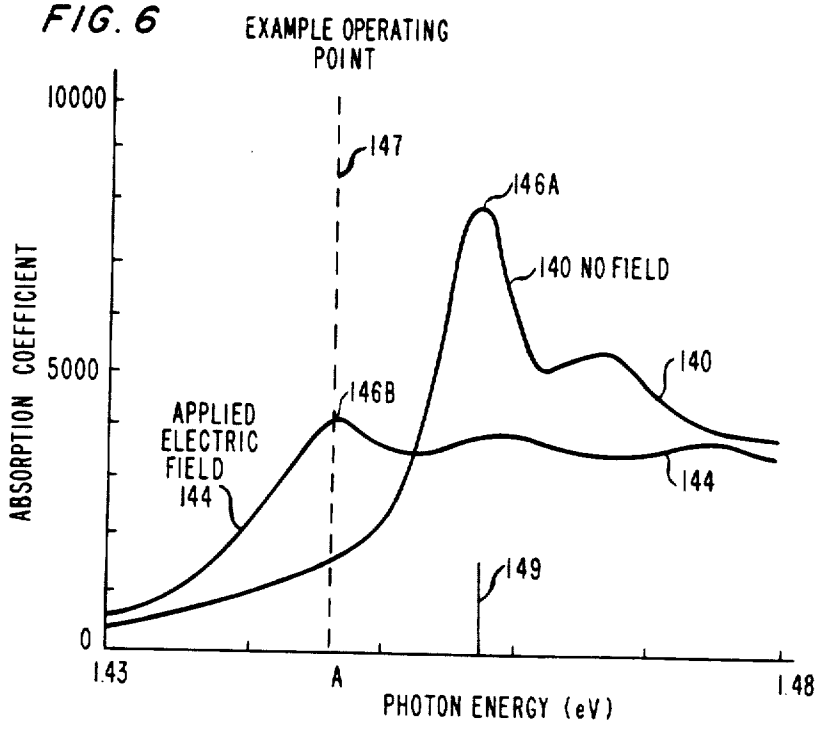

EXAMPLE OPERATING POINT
10000
5000
0
ABSORPTION COEFFICIENT
147
146A
140 NO FIELD
140
146B
APPLIED ELECTRIC FIELD 144
144
149
1.43
A
1.48
PHOTON ENERGY (eV)

FIG. 7

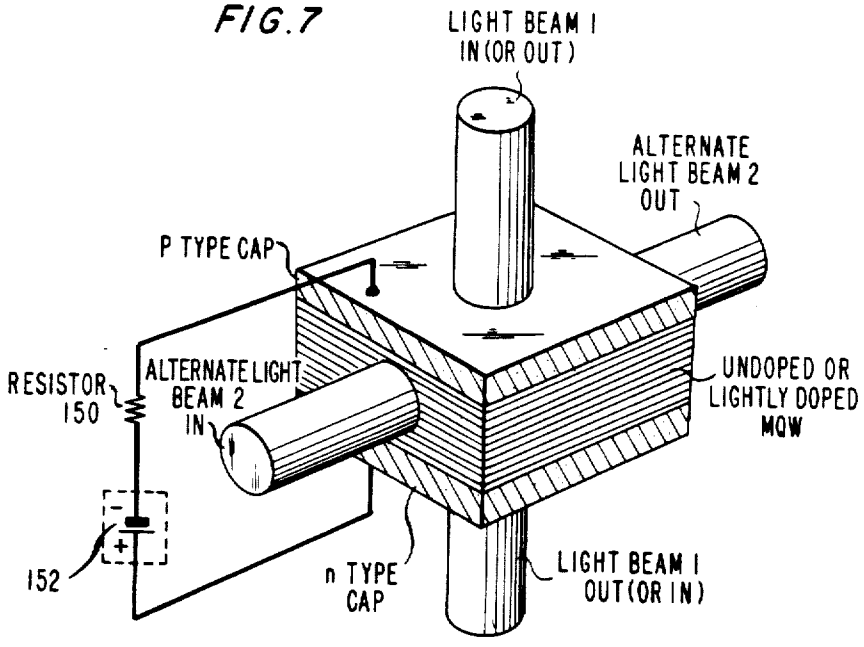

LIGHT BEAM 1 IN(OR OUT)
ALTERNATE LIGHT BEAM 2 OUT
P TYPE CAP
RESISTOR 150
ALTERNATE LIGHT BEAM 2 IN
UNDOPED OR LIGHTLY DOPED MQW
152
n TYPE CAP
LIGHT BEAM 1 OUT(OR IN)

FIG. 8

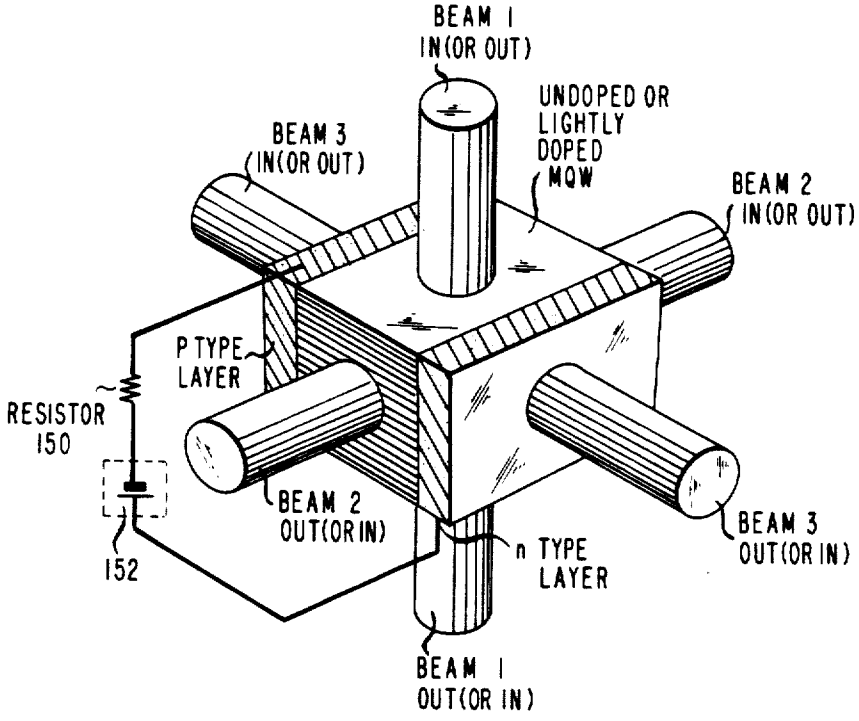

BEAM 1
IN(OR OUT)
UNDOPED OR
LIGHTLY
DOPED
MQW
BEAM 3
(IN(OR OUT)
BEAM 2
IN(OR OUT)
P TYPE
LAYER
RESISTOR
150
BEAM 2
OUT(OR IN)
n TYPE
LAYER
BEAM 3
OUT(OR IN)
152
BEAM 1
OUT(OR IN)

FIG. 9

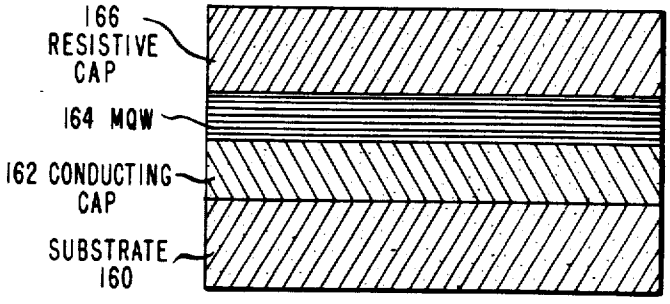

166
RESISTIVE
CAP
164 MQW
162 CONDUCTING
CAP
SUBSTRATE
160

FIG. 10

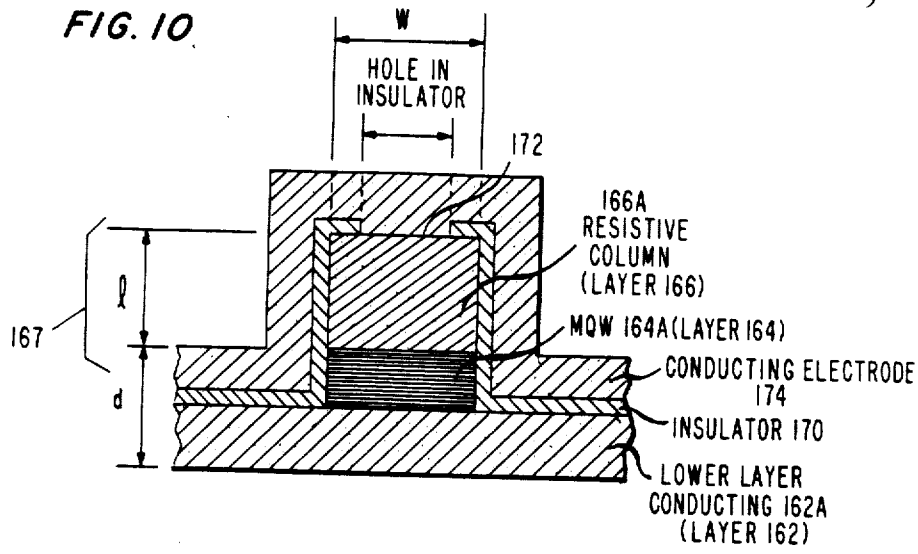

W
HOLE IN INSULATOR
172
166A RESISTIVE COLUMN (LAYER 166)
MQW 164A(LAYER 164)
CONDUCTING ELECTRODE 174
INSULATOR 170
LOWER LAYER CONDUCTING 162A (LAYER 162)
ℓ
d
167

FIG. 11

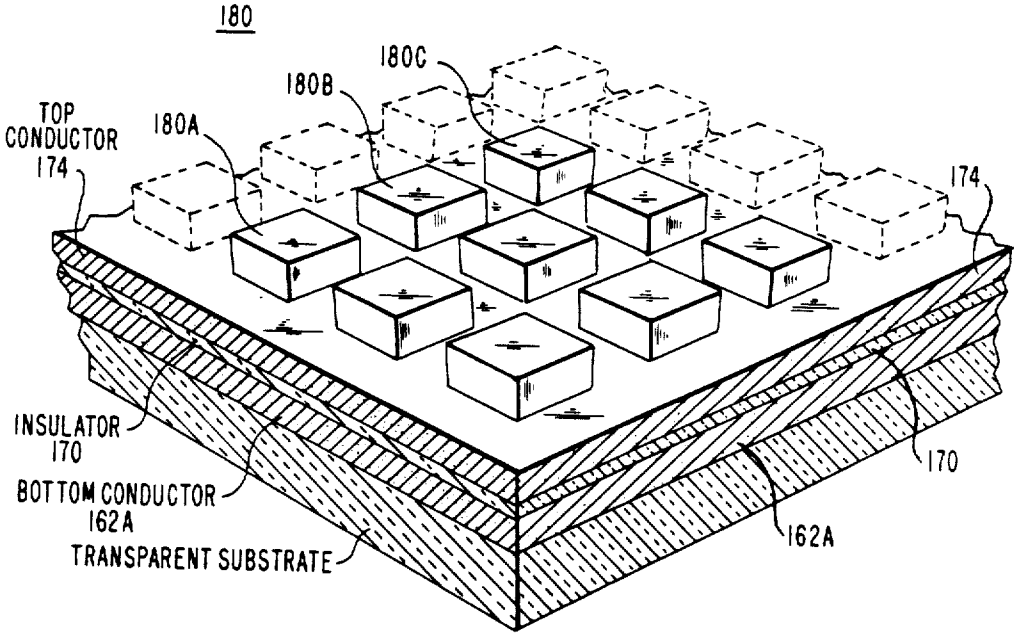

180
180C
180B
180A
TOP CONDUCTOR 174
174
INSULATOR 170
BOTTOM CONDUCTOR 162A
TRANSPARENT SUBSTRATE
170
162A

FIG. 12

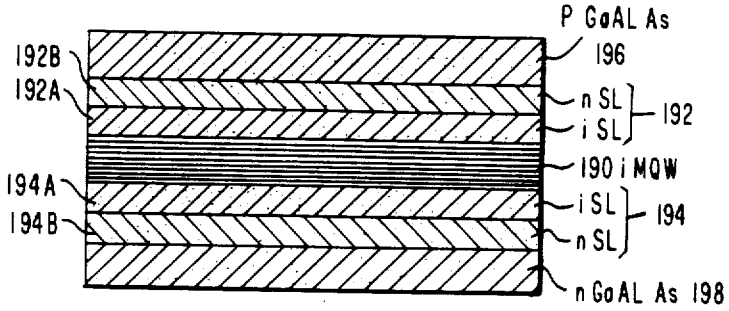


FIG. 13

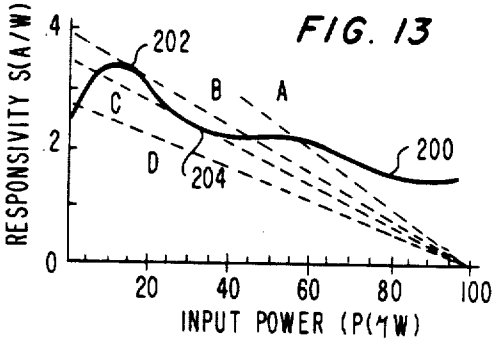


FIG. 14

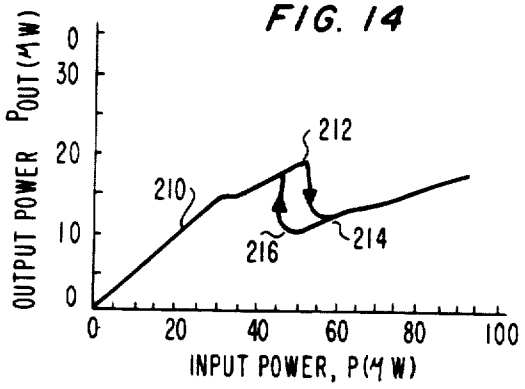


FIG. 15

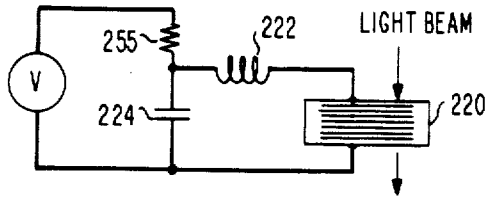


FIG. 16

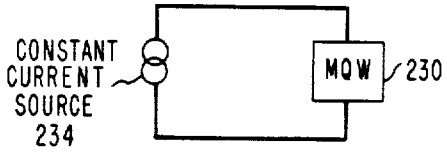


FIG. 17

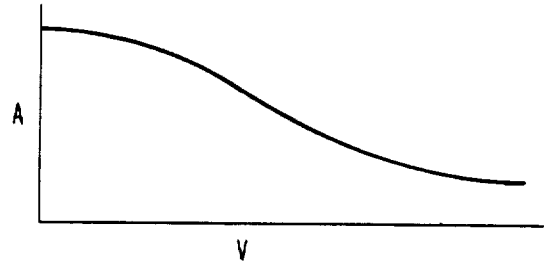


FIG. 18

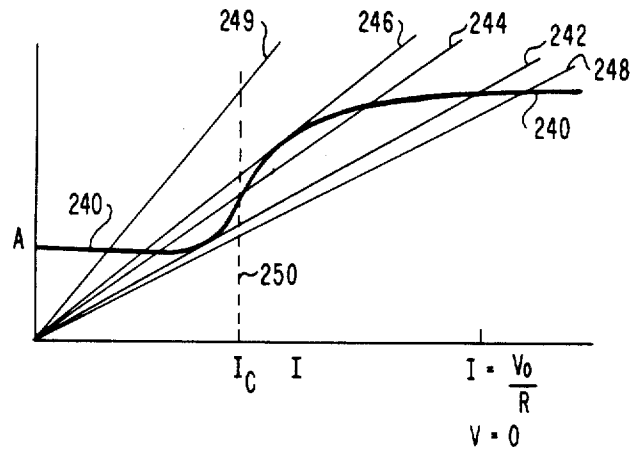

249
246
244
242
248
240
240
A
250
I_C
I
$I = \frac{V_0}{R}$
V = 0

FIG. 19

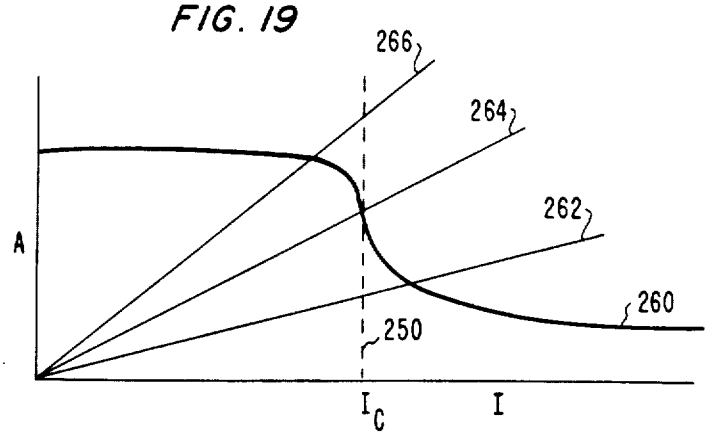

266
264
262
260
A
250
I_C
I

FIG. 20

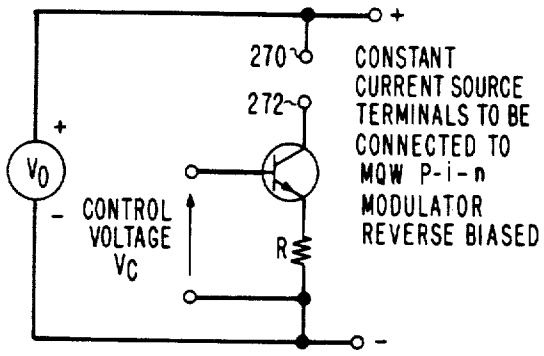

+
270
CONSTANT
CURRENT SOURCE
TERMINALS TO BE
CONNECTED TO
MQW P-i-n
MODULATOR
REVERSE BIASED
272
+
V_0
-
CONTROL
VOLTAGE
V_C
R
-

FIG. 21

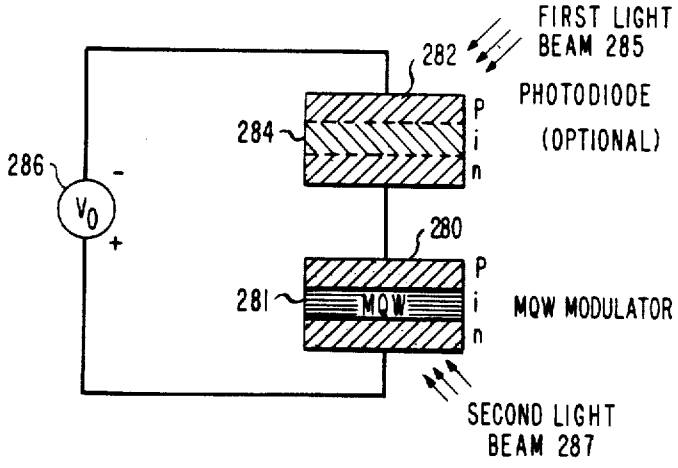

FIRST LIGHT
BEAM 285
282
PHOTODIODE
(OPTIONAL)
284
P
i
n
286
-
V_0
+
280
281
MQW
P
i
n
MQW MODULATOR
SECOND LIGHT
BEAM 287

FIG. 22

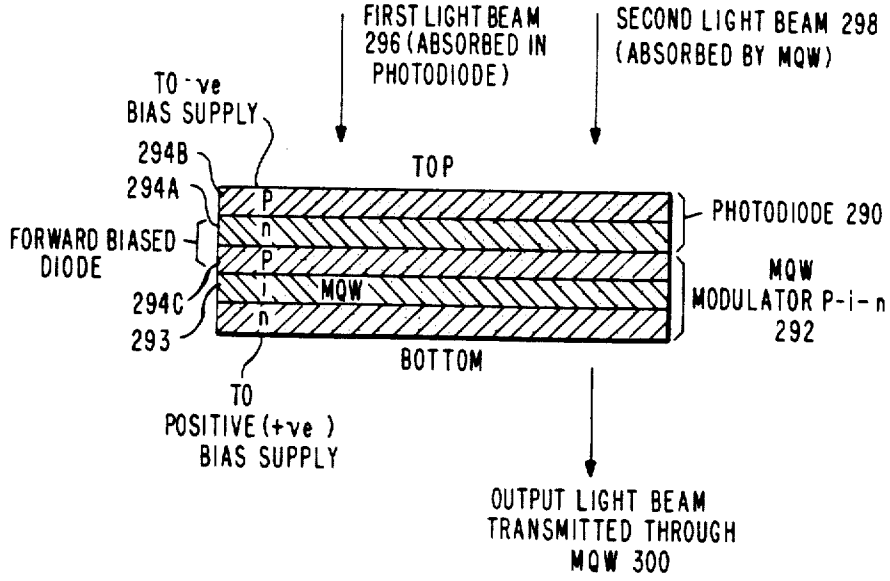

FIRST LIGHT BEAM 296 (ABSORBED IN PHOTODIODE)
SECOND LIGHT BEAM 298 (ABSORBED BY MQW)
TO -ve BIAS SUPPLY
294B
294A
TOP
P
n
P
i
n
MQW
PHOTODIODE 290
FORWARD BIASED DIODE
MQW MODULATOR P-i-n 292
294C
293
BOTTOM
TO POSITIVE (+ve) BIAS SUPPLY
OUTPUT LIGHT BEAM TRANSMITTED THROUGH MQW 300

FIG. 23

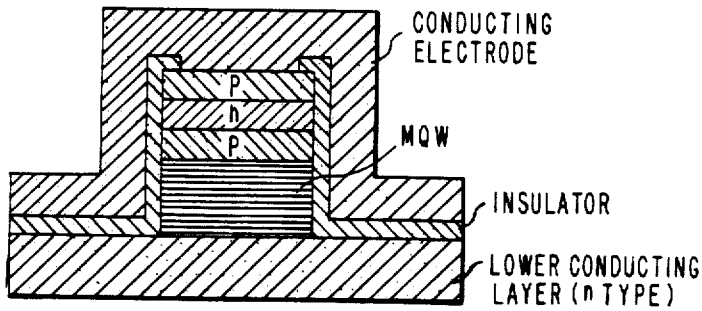

CONDUCTING ELECTRODE
P
n
P
MQW
INSULATOR
LOWER CONDUCTING LAYER (n TYPE)

FIG. 24

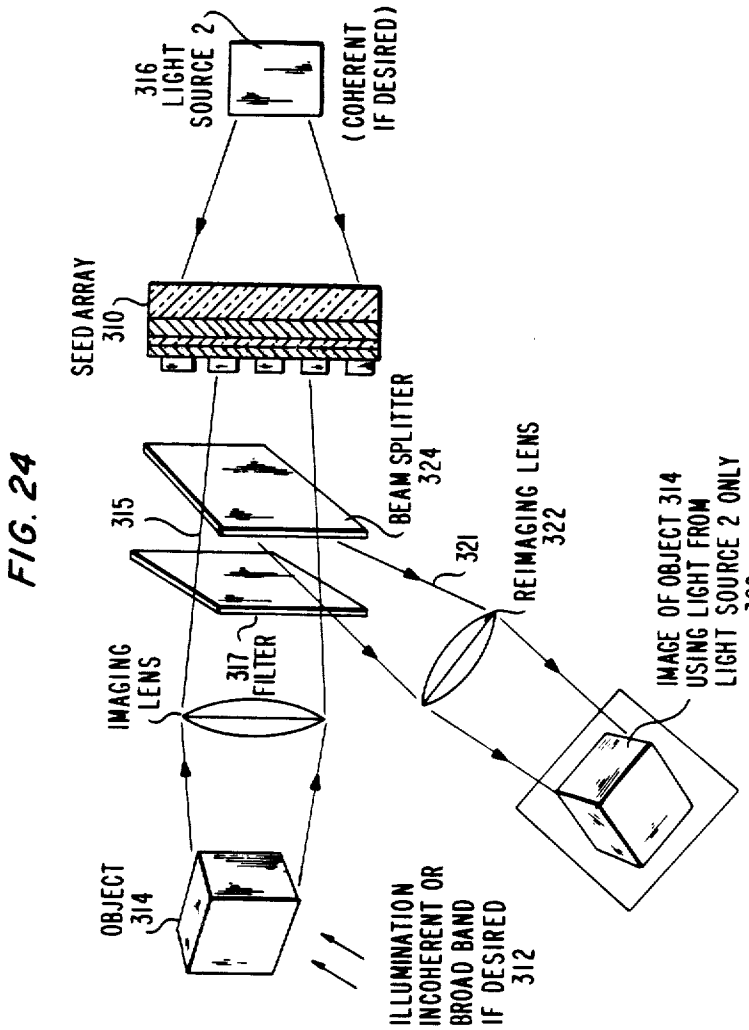

316
LIGHT
SOURCE 2
(COHERENT
IF DESIRED)
SEED ARRAY
310
BEAM SPLITTER
324
315
321
REIMAGING LENS
322
IMAGE OF OBJECT 314
USING LIGHT FROM
LIGHT SOURCE 2 ONLY
320
IMAGING
LENS
317
FILTER
OBJECT
314
ILLUMINATION
INCOHERENT OR
BROAD BAND
IF DESIRED
312

FIG. 25

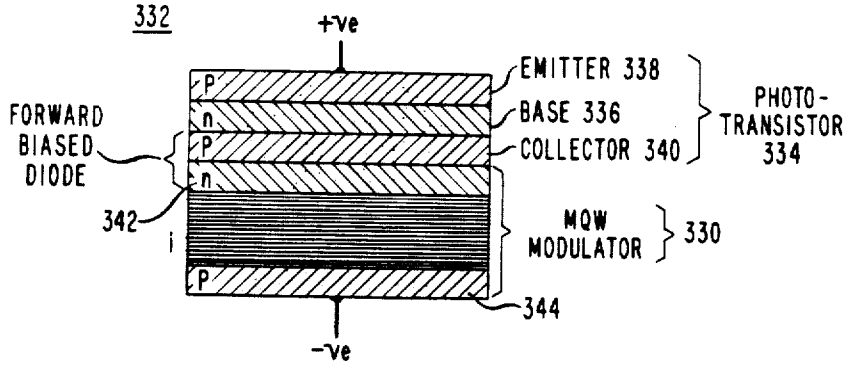

332
+ve
EMITTER 338
BASE 336
COLLECTOR 340
PHOTO-TRANSISTOR 334
FORWARD BIASED DIODE
342
i
MQW MODULATOR
330
344
-ve

FIG. 26

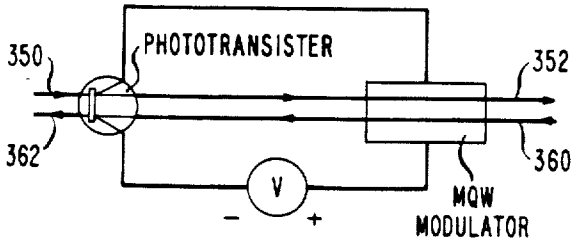
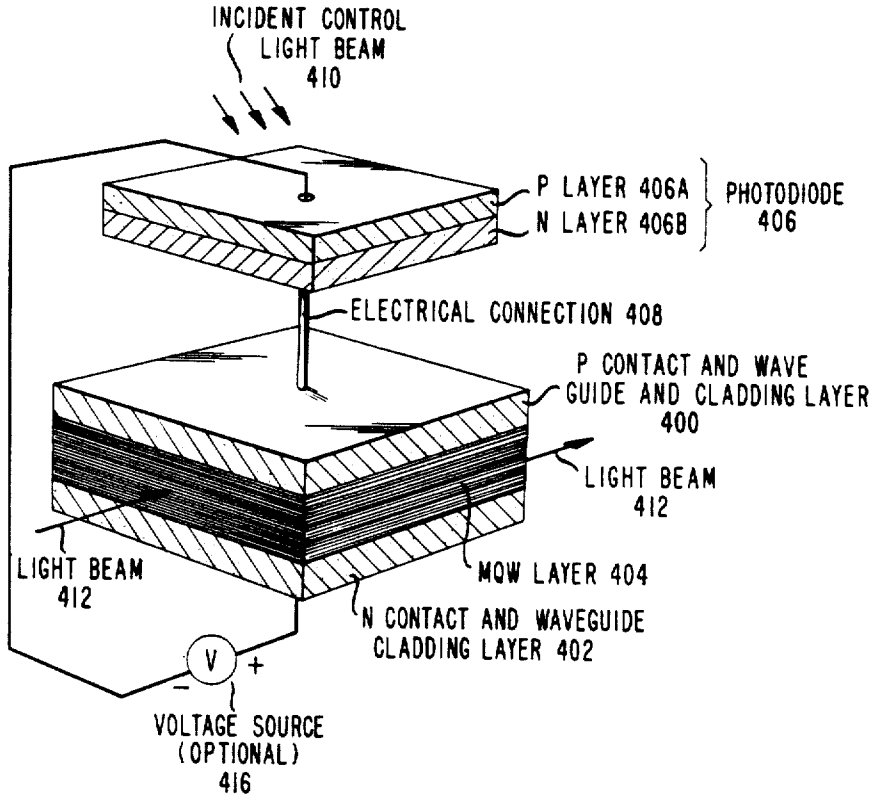

350
PHOTOTRANSISTER
352
362
360
V
MQW MODULATOR

FIG. 27


INCIDENT CONTROL LIGHT BEAM 410
P LAYER 406A
N LAYER 406B
PHOTODIODE 406
ELECTRICAL CONNECTION 408
P CONTACT AND WAVE GUIDE AND CLADDING LAYER 400
LIGHT BEAM 412
LIGHT BEAM 412
MQW LAYER 404
N CONTACT AND WAVEGUIDE CLADDING LAYER 402
V
+
−
VOLTAGE SOURCE (OPTIONAL) 416

NONLINEAR AND BISTABLE OPTICAL DEVICE

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

TECHNICAL FIELD

This invention relates to nonlinear optical devices, particularly to those devices employing high gain or feedback resulting in multistable optical states or other nonlinear optical response.

BACKGROUND OF THE INVENTION

Nonlinear and bistable optical devices for use in computing and switching systems must have a low switching energy. A low switching energy allows many similar devices to be packed into a small volume for parallel processing, and also allows high speed switching to be implemented.

Nonlinear and bistable optical devices have in the past required a high switching energy. They have therefore relied upon the high gain of a high finesse optical cavity such as a Fabry Perot Cavity in order to reduce the switching energy needed for either nonlinear or bistable operation. A bistable optical device having a low switching energy is described by D. S. Chemia-D. A. B. Miller-P. W. Smith in U.S. patent application Ser. No. 566,968. The optical switching energy between bistable states opf the Chemla et al. device was somewhat greater than 100 femtojoules/square micron. However a high finesse Fabry Perot cavity was required in order to achieve this low value of the switching energy in the Chemla et al. device.

SUMMARY OF THE INVENTION

The invention is a nonlinear or bistable optical device having a very low switching energy. The optical switching energy is approximately 4 femtojoules/-square micron and the total switching energy, including electrical energy, is approximately 20 femtojoules/-square micron. The low switching energy is achieved by the use of a material capable of absorbing light and thereby generating photocurrent. A voltage responsive to the photocurrent is applied to a structure having a semiconductor quantum well region in order to cause the optical absorption of the semiconductor quantum well region to vary in response to variations in the photocurrent. Also the variations in absorption in the semiconductor quantum well region may influence the absorption of the material capable of absorbing light so as to provide a feedback path resulting in nonlinear and bistable optical operating conditions.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram showing the invention.

FIGS. **2** and **3** are graphs showing operating characteristics of the invention.

FIG. **4** is a graph showing an optical transmission of the invention.

FIG. **5** is a side view showing the invention.

FIG. **6** is a graph showing an optical absorption coefficient of the invention.

FIG. **7** and FIG. **8** are isometric schematic views showing the invention.

FIG. **9** and FIG. **10** are side views showing making the invention.

FIG. **11** is an isometric view showing the invention as an array of discrete devices.

FIG. **12** is a side view showing the invention employing a pin diode structure.

FIG. **13** and FIG. **14** are graphs showing operating characteristics of the invention.

FIG. **15** is a schematic diagram showing the invention using an inductance coil to make an optical oscillator.

FIG. **16** is a schematic diagram of the invention using a constant current source.

FIG. **17**, FIG. **18**, and FIG. **19** are graphs showing operating characteristics of the invention.

FIG. **20** is a schematic diagram showing the invention using a transistor.

FIG. **21** is a schematic diagram showing the invention using a photodiode.

FIG. **22** is a side view showing the invention in an integrated structure with a photodiode or a phototransistor.

FIG. **23** is a side view showing the invention.

FIG. **24** is a schematic diagram showing the invention as a spatial light modulator.

FIG. **25** is a side view of the invention integrated in a semiconductor body with a transistor.

FIG. **26** is a schematic diagram showing the invention having the same light beam acting on a phototransistor and a MQW modulator.

FIG. **27** is an isometric view showing the invention with a waveguide.

DETAILED DESCRIPTION

FIG. **1** is a schematic diagram of an exemplary embodiment of the invention. Light source **100** generates the input light beam **102** which is incident upon material **104**. A fraction of input light beam **102** emerges from material **104** as output light beam **106**. Material **104** may be a single material structure or material **104** may have a number of components such as an electronic circuit.

The optical characteristics of material **104** are set out in FIG. **2** and FIG. **3**. The principles of optical absorption exhibited by material **104** are: first, that an increasing intensity of input light beam **102** leads to an increasing absorption coefficient by material **104**; and second, a positive feedback mechanism is exhibited by material **104** such that increasing absorption of light energy by the material **104** leads to an increasing optical absorption coefficient. As a consequence of these two principles the material **104** switches between stable optical stages of transmission.

The behavior of material **104** under variations in intensity of input light beam **102** is given in FIG. **2**. However in the following discussion the units of beam power are used rather than intensity. Beam power is expressed in units of Watts and beam intensity in units of Watts per square meter. Beam power is the integral of intensity over a cross section perpendicular to the axis of the light beam. Units of power are more useful in the following discussion because material **104** responds to beam power, and more particularly to power absorbed by material **104**. In FIG. **2**, the power in input light beam **102** is plotted along the horizontal axis. Along the vertical axis the power in output light beam **106** is plotted as transmitted power. At an input power of value A, the transmitted power is given by a value of TA, as shown in FIG. **2**. As the input power is increased to a

value of B, the transmitted power increases to a value of TB1. However the absorption coefficient of material **104** increases with increasing input power, and therefore the transmission curve **109** from input power A to input power B is below a line of constant slope such as line **110**. A further increase of input power from value B to value C results in a further increase in absorption coefficient so that the transmission of material **104** becomes unstable and switches from a value of TC1 to a value of TC2. A further increase of input power to a value of D leads to a value of transmission such as the value TD.

Decreasing the intensity of light beam **104** results in the transmitted power tracing along the curve **109** to input power B, whereupon the absorption coefficient of material **104** switches to a smaller value, and the transmitted power increases to the value TB1. Material **104** is said to exhibit optical bistability because material **104** switches from a state of high transmission to a state of low transmission as the optical input power is increased, and switches back to high transmission as the optical input power is decreased. However, optical bistability may exist for other sequences of switching.

FIG. **3** gives an exemplary set of characteristics of material **104** which lead to optical bistability. The optical absorption is assumed to be a function of material excitation. Also the material excitation is assumed to be a function of optical power absorbed by material **104**. These two assumptions lead to two simultaneous equations whose graphical solution is shown in FIG. **3**. Let A represent the optical absorption and let N represent the material excitation. The first assumption is expressed generally by Equation (1).

$$A=A(N) \tag{1}$$

In FIG. **3** transmission, represented by T, is plotted, and T is defined as:

$$T=1-A. \tag{2}$$

The plot of transmission T versus material excitation N from Equation (1) is shown by curve **120**. Curve **120** shows an increasing optical absorption, hence a decreasing transmission T, as the material excitation N increases.

The second assumption, expressed in Equation (3), is that material excitation N is proportional to the absorbed power. The incident optical power is represented by P and so the absorbed optical power is AP, giving for the material absorption:

$$N=yAP. \tag{3}$$

The symbol y represents a proportionality constant. In FIG. **3** straight lines are obtained by plotting Equation (3) as transmission T versus material excitation N for fixed values of input power P. Straight lines are plotted in FIG. **3** for values of input power shown in FIG. **2** as values A, B, C, and D, and the straight lines of FIG. **3** are correspondingly labeled A, B, C, and D.

The intersection **120A** of curve **120** and line A gives the transmitted power shown as TA in FIG. **2**. There are two intersections of curve **120** and line B in FIG. **3**, corresponding to the two points TB1 and TB2 of FIG. **2**. Line C is drawn tangent to the upper portion of curve **120** (the value C of input power was chosen so that this tangent condition would occur) represented by point TC1 in FIG. **2**. Also line C intersects curve **120** at the point corresponding to TC2. Material **104** is unstable when the intensity of input light beam **102** reaches the power represented by value C, and so material **104** switches from transmitted power TC1 to the value given by TC2. A further increase in input power to the value represented by line D in FIG. **3** gives only one intersection between curve **120** and line D, represented by point TD in FIG. **2**.

An exemplary embodiment of a material which exhibits bistable switching characteristics and uses sample temperature as the material excitation N, is a GaAs/-GaAlAs multiple quantum well (MQW) sample. Hereinafter a multiple quantum well structure is referred to as a MQW structure. MQW structures are more fully disclosed in the U.S. patent applications: D. S. Chemla-P. A. B. Miller-P. W. Smith, Ser. No. 567,222; D. S. Miller-D. A. B. Miller-P. W. Smith, Ser. No. 566,968; and D. S. Chemla-T. C. Danen-A. C. Gossard-D. A. B. Miller-T. H. Wood, Ser. No. 558,545. The sample included 375 periods of $Ga_{0.7}Al_{0.3}As$ layers, 87 Angstroms thick, alternating with 85 Angstrom thick GaAs layers, with this whole structure sandwiched between approximately 1.2 micron thick $Ga_{0.7}Al_{0.3}As$ cap layers, giving a total thickness of approximately 9 microns. The sample was epoxied to a glass fiber in order to provide a mounting with low thermal conductivity. Input light beam **102** was supplied by a laser. The laser wavelength was chosen at a photon energy lower than the exciton resonant peak, but close enough to the peak so that a temperature rise of the sample resulted in the exciton peak shifting into the laser wavelength region, thereby increasing the absorption coefficient of material **104**. Thus an increasing temperature of the sample led to an increasing optical absorption. And an increasing absorption led to an increasing sample temperature, which led to an increasing optical absorption. The sample exhibited optical bistable switching as shown in FIG. **2**.

FIG. **4** shows the optical transmission coefficient of the MQW sample for room temperature at curve **124** and for an elevated temperature by curve **126**. The sample was heated to the elevated temperature by absorption of energy from input light beam **102**. The laser photon energy is shown by line **128**. The sample transmission coefficient decreases from a value **130** to a value **132** as the sample temperature rises, caused by a shift in the optical absorption from curve **124** to curve **126**. Thus the sample exhibits optical bistability as discussed above.

FIG. **5** is a schematic diagram of an exemplary embodiment of the invention as a self-electro-optic effect device (hereinafter a SEED device). The elements of FIG. **5** are labeled in accordance with FIG. **1**. Input light beam **102** is directed at material **104**. Material **104** includes a MQW structure having electrical contacts **104A**, **104B** which are in electrical connection with an electronic circuit **104C**. The electronic circuit responds to photocurrent produced by absorption of light within the MQW structure and in turn applies a voltage to the MQW and thereby influences the optical absorption properties of the MQW. The name SEED is used for the embodiments of the invention shown in FIG. **5** because the photocurrent produced within the MQW is used to influence the properties of the MQW, hence "self" electro optic effect device. The electronic circuit may be a simple resistor, a coil, supplying inductance, a photodiode, a phototransistor, a constant current

source, or other useful electronic circuit. Also the electronic circuit may be made of separate components or it may be integrated into the semiconductor wafer including the MQW structure. A description of a number of embodiments of the invention employing a MQW structure follows.

The following exemplary embodiments of the invention include a MQW structure as a light absorber. A reason for using a MQW structure as the light absorber is that a small voltage applied to electrical contacts attached to a MQW structure results in a large change in the optical absorption properties of the MQW structure. The influence of an applied voltage on the optical properties of a MQW structure are more fully disclosed in U.S. patent application by Chemla et al. Ser. No. 558,545 mentioned hereinabove. A brief discussion of the influence of an electric field upon the properties of a MQW is aided by reference to FIG. **6**. The curves in FIG. **6** show the optical transmission of an undoped (intrinsic) MQW structure with different values of electric field applied to the MQW. The MQW was not intentionally doped, and the level of background doping impurities was less than approximately $5*10^{15}cm^{-3}$. The electric field was applied by sandwiching the intrinsically doped MQW between a p doped contact, **104A**, and an N doped contact **104B**. The MQW then served as the intrinsic (i) region of a pin diode. The pin diode was backbiased in order to shift the diode "built in field" completely into the MQW layer region. The optically active MQW region can be switched from a low electric field at 0 applied Volts as shown in curve **140** to a field of approximately $7.3*10^4V/cm$ as shown in curve **144** by the external application of approximately 8 Volts across the p and n contacts **104A** and **104B**. The optical absorption is increased dramatically at the exemplary operating point chosen at photon energy A, when the electric field is applied to the MQW. The heavy hole exciton resonance **146A** at zero applied voltage shifts to resonance peak **146B** at the applied electric field of $7.3*10^4V/cm$.

FIG. **7** and FIG. **8** show an exemplary embodiment of the invention having a MQW as the intrinsic region (i) of a pin diode, with the electronic circuit **104C** being a simple resistor **150** and a voltage source **152**. Voltage source **152** is optional, and is set to zero Volts for the following discussion. In FIG. **7** the p and n electrical contact layers are parallel to the layers of the MQW. In FIG. **8** the electrical contact layers are perpendicular to the layers of the MQW. For the embodiments having light beams perpendicular to the layers of the MQW, the cap layers must be transparent at the operating wavelengths. For embodiments having light beams parallel to the layers of the MQW, it may be necessary to have only one or two quantum well layers, rather than a multiple number. However the name MQW will be used to include structures having only one or two quantum well layers. In operation, the diode has a built in electric field. The layers of the pin structure are arranged so that in the absence of an externally applied voltage, the MQW lies substantially within the "built in field". Thus in the absence of a light beam the MQW will have an optical absorption altered from its zero electric field value. On applying an optical beam which is partially absorbed by the MQW layers, electrons and holes are created. The electrons and holes move in such a way in the electrical circuit as to partially cancel the "built in field". Thus the electric field across the quantum wells will be reduced. This reduction in electric field applied to the quantum wells will in turn alter the absorption and refraction of the quantum wells. Embodiments of the invention are also possible in which the MQW structure is not contained in a pin diode configuration, in which case the contact regions in FIG. **7** and FIG. **8** need not be p and n doped.

A numerical example based on the embodiment of FIGS. **7** and **8** shows that a 1 milliwatt light beam of 1.5 eV photons will produce a photocurrent of approximately 0.66 mA, assuming unit quantum efficiency (all of the light absorbed). For a resistor of 1000 Ohms, this current will produce a voltage drop of 0.66 Volt. Such a voltage will reduce the "built in field" for a semiconductor with a 1.5 electron volt bandgap by approximately $(1.5-0.66)/1.5$, a factor of approximately 0.56. Such a large change in the electric field applied to the MQW structure produces a significant change in the optical absorption and the index of refraction. The response time of a device having a 10 micron × 10 micron × 1 micron volume with electrodes parallel to the MQW planes and the 10 micron faces may be estimated. The capacitance of the device is approximately $1.2*10^{-14}$ Farad for a dielectric constant of 13. With a 1000 Ohm resistor, the RC time constant is approximately 12 picoseconds, and this time is comparable to the sweep out time for a 1 micron thick device.

Also a direct current reverse bias may be applied to the p and n contacts by using the optional voltage source **152**. The photocurrent will alter the "built in field" and modify the optical absorption and transmission of the MQW layers.

An example of absorptive optical bistability based on an exemplary embodiment of the invention has the electro optical absorption characteristics shown in FIG. **6**. Absorptive bistability is based upon a reduction in absorption with increasing optical intensity. A MQW structure is placed within a Fabry-Perot cavity formed, for example, from mirrored electrodes. As the intensity of the light beam is increased from zero, absorption occurs in the MQW material. This absorption produces a photocurrent. The photocurrent gives a voltage drop across the resistor **150**, which reduces the voltage across the MQW, thereby reducing the applied electric field within the MQW and moving the absorption spectrum from curve **144** towards curve **140**. The absorption within the MQW is thereby reduced. As the absorption inside of the Fabry-Perot cavity is reduced, the cavity quality factor increases giving more resonant built up optical field within the cavity. With a saturable absorber this process has a positive feedback, the process becomes regenerative, and the cavity switches on with increasing incident intensity. Using this exemplary embodiment of the invention, the absorption is saturable and bistable switching occurs.

An example of refractive bistability based on an exemplary embodiment of the invention having the electro optical absorption characteristic shown in FIG. **6** follows. Refractive bistability is based upon a change in refractive index with increasing optical intensity. A MQW structure is placed within a Fabry-Perot cavity formed, for example from mirrored electrodes. As the intensity of the light beam is increased from zero, absorption occurs in the MQW material. This absorption produces a photocurrent. The photocurrent gives a voltage drop across the MQW, thereby reducing the applied electric field within the MQW and moving the absorption spectrum from curve **144** towards curve **140**. The resulting change in absorption spectrum also

changes the refractive index of the MQW as can be described through the Kramers-Kronig relations. This change in refractive index changes the resonant condition of the cavity because it changes the optical path length inside the MQW. With appropriately chosen operating wavelength, this change in refractive index will move the cavity towards the resonant condition with a consequent further increase in optical intensity inside the cavity. A further increase in intensity gives increased photocurrent and hence further change in refractive index, and hence the device can switch into a near resonant condition due to such a regenerative process. Using this exemplary embodiment of the invention, the refractive index depends on the incident optical power and bistable switching occurs.

Whether the device operates through absorptive or refractive bistability or some combination of the two depends upon the choice of wavelength and other parameters.

The presence of an applied voltage produced by optional battery **152** has several advantages including: the presence of an electric field which helps to sweep out charge carriers from the MQW, thereby making switching faster, and the ability to tune the operating point by shifting the absorption spectrum towards curve **140** or towards curve **144**.

FIGS. **9** and **10** show steps for growing an exemplary integrated embodiment of the invention. In FIG. **9** substrate **160** has first a conducting cap layer **162** grown upon it. Then a MQW structure **164** is grown upon the conducting cap layer **162**, and finally a resistive cap layer **166** of controlled thickness is grown upon MQW structure **164**. A mesa **167** of the layers shown in FIG. **9** is produced by etching, an insulating layer **170** is deposited over the mesa, and a hole **172** is produced in the insulating layer so as to expose the top of resistive cap layer **166**. In the mesa, resistive cap layer **166** becomes resistive column **166** A. Finally a conducting electrode **174** is deposited over insulating layer **170**, thereby providing electrical contact to resistive column **166A** through hole **172**. A potential may be applied to the MQW **164A** by making electric contact to conducting layers **174** and **162A**. The substrate may be removed if it is not transparent at the operating wavelength. The resistive column **166A** has a length l and width w, and its resistance is easily controlled by control of l and w and also the doping concentration used when manufacturing layer **166**. Resistive column **166A** serves as resistor **150** as shown in FIGS. **7** and **8**. An exemplary embodiment of the invention using zero bias may be made by simply electrically connecting electrode **174** with conducting layer **162A**. Alternatively, a voltage source such as a battery **152** may be connected between conducting electrodes **174** and **162A**.

FIG. **11** shows an exemplary embodiment of the invention as an array **180** of devices such as the one shown in FIG. **10**. The process steps used in making the one device shown in FIG. **10** are particularly well suited to make an array of devices as shown in FIG. **11**. Layers in FIG. **11** are given reference numbers assigned to the corresponding layers shown in FIG. **10**. Each individual device in the array, such as **180A**, operates independently of all other devices in the array. This independence results from the electrical independence of each device in the array, and from the fact that each device has its own load resistor **166A**. Also if an external electric voltage is applied to devices **180A**, **180B**, **180 C** . . . , then only two connections need be made to array **180**, and all devices are connected through electrodes **174** and **162A**. Devices **180A**, **180B**, **180C** . . . may be used to perform parallel processing on independent light beams, and the logic performed by each device is independent of the logic performed by any other device. For example, more than one independent light beam may be directed at each device **180A** . . . in order to perform AND or OR logic using the bistable properties or other properties of the devices. Also arrays **180** may be stacked one upon the other to perform further logic operations.

An exemplary embodiment of the invention was made using the circuit shown in FIG. **7**, choosing the battery polarity so as to reverse bias the pin diode, using a light beam perpendicular to the MQW layer planes, and using a semiconductor body shown in FIG. **12**. The MQW layers **190** are 50 GaAs quantum well layers of 95 Angstrom thickness separated by 98 Angstrom GaAlAs barrier layers, all with no intentional doping. The total MQW thickness is approximately 0.96 micron. Supperlattice buffer layers **192**, **194** were used to protect the intrinsic doped MQW layers **190** from doping in the contact layers. Superlattice buffer layers **192**, **194** are 0.29 microns thick, with layers of GaAs of thickness 28.5 Angstroms thick alternating with 68.5 Angstrom GaAlAs layers. Layers **192A** adjacent to the MQW **190** are undoped, that is they have intrinsic or background doping. Layers **192B** have p doping for contact with the p doped contact layer **196**. Layer **196** is $Ga_{.68}Al_{.32}As$ of 0.98 microns thickness and has p doping concentration of approximately $5*10^{17}cm^{-3}$. Layers **194A** are undoped, that is they have intrinsic doping for contact with MQW **190**. Layers **194B** have n doping for contact with the n doped contact layer **198**. Layer **198** is also $Ga_{.68}Al_{.32}As$ of 0.98 micron thickness and has an n doping having a concentration of approximately $5*10^{17}cm^{-3}$. The intrinsic layers have a p type background doping of approximately $2*10^{15}cm^{-3}$. This device was grown by molecular beam epitaxy on a Si doped [100] GaAs substrate (not shown). The device was defined laterally by an approximately 600 micron diameter mesa etched from the layers. A small hole was etched through the opaque substrate (not shown) by a selective etch. Metal contacts were electrically attached to the doped contact layers **196**, **198**. The capacitance of the device is approximately 20 pF.

The structure forms a pin diode with the MQW layers **190** within the intrinsic (i) layer. The active layer can be switched from a low field to approximately $7.3*10^4$ Volts/cm by the application of approximately 8 Volts between layers **196**, **198**. The sample used is described in detail in the article by Wood et al. in Applied Physics Letters, Vol. 44, page 16, 1984.

When a reverse bias is applied to the semiconductor structure shown in FIG. **12**, then an electric field is applied to MQW layers **190** and the absorption spectrum near the bandgap shifts to lower energies with some broadening of the exciton peak, as shown in FIG. **6**. A photocurrent is produced by this light absorption. In reverse bias approximately one photocarrier is collected for every photon absorbed. Only at reverse bias less than approximately 2 Volts does the quantum efficiency drop off, probably because the depletion region does not then extend all the way through the MQW.

The responsivity S of the semiconductor structure shown in FIG. **12** is given as a curve **200** in FIG. **13**. The responsivity S is the photocurrent produced per unit of incident light power, and is expressed in the units

of Amperes per Watt of incident light power. Curve **200** shows the responsivity S for a laser used as the light source, and the laser turned to a photon energy of 1.456 eV (851.7 nm). This photon energy is approximately the heavy hole resonance energy at conditions of zero bias for the MQW structure used. As the reverse bias is increased, the responsivity first increases as photocurrent collection becomes complete, and then decreases as the exciton absorption peak moves to lower energy, as shown in FIG. **6**. The subsequent "bump" between 8 V and 16 V in curve **200** is due to the light hole exciton resonance similarly moving past the measuring wavelength.

The input-output characteristics of the device when connected to a resistor between the device and the source of potential as shown in FIG. **7**, may be calculated with the aid of a graphical solution of two simultaneous equations. The graphical solution is similar to the solution of Eq. 1, Eq. 2 and Eq. 3, as discussed hereinabove, and as shown in FIG. **2** and FIG. **3**. The first equation is the measured responsivity of the MQW structure as shown in FIG. **13** as curve **200**, and which relationship is written in a general form as:

$$S=S(V) \tag{4}$$

The second equation is $V=V_O-RSP$, where P is the optical input power and V is the voltage across the diode, when written as:

$$S=(V_o-V)/RP \tag{5}$$

The straight lines given by Eq. 5 are shown plotted as dashed lines in FIG. **13**, for different values of the product RP. Straight lines A and D have only one intersection with curve **200**, and represent stable operating points. Straight lines B and C have tangent points **202** and **204** with curve **200**. The tangent points **202**, **204** represent unstable switching points. All straight lines between lines B and C have three intersection points with curve **200**, and the middle point represents unstable operation.

In FIG. **14** bistable switching of the device is shown. As input power is increased the output power increases along curve **210** up to the point **212**. As the input power passes point **212** the operating point reaches a tangent point **204**, the device becomes unstable and switches to point **214**, a state of low transmission. Further increases in input power lead to increases in output power. Reducing input power leaves the device in the state of low transmission until the operating point reaches the other tangent point **202**, at which input power, represented by point **216**, the device switches to a state of high transmission. The bistable operation of this device is similar to the operation outlined in FIG. **1**, FIG. **2**, and FIG. **3**, where here the material excitation N is the photocurrent.

Table 1 shows values of switching power, switching time, RC time constant, and switching energy obtained with the device shown in FIG. **12** and FIG. **7**.

TABLE 1

Resistance megohm	Switching Power micro-watt	Switching Time micro-second	Time Constant micro-second	Switching Energy nano-joule
100	0.67	1,500	2,000	1.0
10	6.5	180	200	1.2
1	66.	20	20	1.3
0.1	660.	2.5	2.	1.7
.022	3,700	.4	.44	1.5

The device operates over a broad range of parameters, as can be seen from Table 1. The switching power and speed can be chosen over a range of nearly 10^4, as shown in Table 1. Optical bistability occurs over a range of voltages from 15 Volts through the highest used, 40 Volts. The device operation is insensitive to spot size from less than a 10 micron diameter spot size up to the maximum used of 100 microns diameter. And this insensitivity to spot size is as expected for a device responsive to optical power, as is the exemplary device. Optical bistability was also observed over a range of operating wavelengths of 850 to 860 mm.

The device does not require any time varying voltages for its operation. However increases and decreases of approximately 0.8 Volt can switch the device from high to low transmission, respectively, near 20 Volts bias.

The device is large (600 microns) by optical standards and consequently has a large capacitance and a moderately low switching energy. The observed values of switching energy are approximately 1 nanojoule incident optical energy and less than 4 nanojoule dissipated electrical energy at 20 Volts bias. The switching energy per unit area is approximately 4 femtojoules per square micron incident optical energy and approximately 14 femtojoules per square micron electrical energy. With smaller devices faster and lower energy operation is possible.

An exemplary embodiment of the invention as a negative resistance oscillator is shown in FIG. **15**. The semiconductor structure **220** shown in FIG. **12** was connected in a circuit containing an induction coil **222** of approximately 97 millihenry, a capacitor **224** of 1 microfarod, and a resistor **225** of 100 kilohms, as shown in FIG. **15**. The intrinsic capacitance of approximately 20 pF of the semiconductor structure **220** together with other stray capacitances and the 97 millihenry induction coil **222** form a LC circuit which operates with the semiconductor structure as a negative resistance amplifier. The 1 microfarad capacitor **224** serves as an AC short on the bias supply. With 7 volts reverse bias, and 70 microwatts of steady laser power at 851.6 nanometers the circuit oscillated at a frequency of approximately 56 kilohertz. The transmitted light beam was detected by an avalanche photodiode. The intensity of the transmitted light beam varied at the oscillation frequency and an electrical signal measured between conductive cap layers **196**, **198** varied at the oscillation frequency.

An exemplary embodiment of the invention using a constant current source is shown in FIG. **16**. The MQW **230** may serve both as a light modulator and a light detector, and the response of the MQW depends upon the voltage applied across the MQW. The absorption of the MQW, represented by A, may either increase or decrease with increasing voltage applied to the layers of the MQW. Whether the absorption A increases or decreases with voltage applied to the MQW depends upon a number of factors, including the light wavelength

operating point, the location of the "built in field" when the MQW is mounted in a pin diode structure, and the movement of the "built in field" under the influence of an applied external voltage. FIG. **6** shows an example of an operating point, labeled A, having an increased absorption with increased electric field applied to the MQW layers. For cases in which the internal electric field increases with applied external voltage, then the example operating point A in FIG. **6** gives increasing absorption with increasing external voltage. However if an operating point **149** near the 0 field exciton peak **146**A is chosen, the absorption decreases with increasing applied voltage.

A first example has a MQW structure in which the optical absorption decreases with increasing voltage as shown in FIG. **17**. A constant current source is a source whose current is independent of the voltage across the load. The load in this example is the MQW structure. One way of modeling a constant current source is to approximate it by a large voltage source V_O in series with a large resistor R. When the voltage across the load is low compared to the hypothetical voltage V, then the current through the load is approximately constant at a value $I_c=V/R$. This approximation becomes arbitrarily exact as V and R tend to arbitrarily large numbers. The constant current source of FIG. **16** will therefore be approximated as a battery of voltage V_O and a resistor of resistance R. Then the absorption A as a function of current I in the circuit increases with current as shown by curve **240** in FIG. **18**, because the current I flowing in the circuit is photocurrent and:

$$V=V_O-IR \tag{6}$$

In equation (6) V is the voltage applied to MQW **230**, V_O is the potential supplied by the constant current source **234** model battery (not shown), and R is the resistance of the resistor used in the model constant current source. The photocurrent I flowing in the circuit is given by:

$$I=yAP. \tag{7}$$

In equation (7) P is incident optical beam power and y is a proportionality constant. Plots of A versus I using Eq. 7 are shown in FIG. **18** as straight lines **242, 244, 246, 248,** and **249**. The device operating point is determined by the simultaneous solution of A versus current given by curve **240** and the straight lines given by Eq. 7. Lines such as lines **244** have three points of intersection with curve **240** and hence represent unstable solutions which lead to optical bistability. Lines **242** and **246** have a tangent point and represent unstable switching points. Lines **248, 249** have only one point of intersection with curve **240** and so represent stable operating points. As V_O and R are made large, the characteristic **240** of A versus I can become very steep at I_c. The value I_c is shown as line **250**. An advantage of the constant current source is that it is easier to obtain the necessary multiple intersections of straight lines and curve **240** because the curve **240** is steepened relative to the curve obtained with a constant potential source. Thus bistability can be obtained even for absorptions A which change comparatively slowly with voltage V across the MQW structure.

A second example of a constant current driven MQW SEED device has a structure in which the optical absorption A increases with increasing voltage. The optical absorption A then has the general form as a function of current I as is shown in FIG. **19** by curve **260**. Straight lines **262, 264, 266,** are plotted in FIG. **19** from Eq. 7. All lines from Eq. 7 have only one intersection with curve **260** and so represent stable operating points. The photocurrent created by power absorbed in the MQW passes through the constant current source **234**. The constant current source **234** may be set to attempt to make a "set" current I_c pass through MQW **230**. If the light power is very low and the photocurrent is below the set current then the constant current source attempts to adjust the photoabsorption to increase the photocurrent, but because of the low light power the constant current source is unable to achieve raising the photocurrent to equal the "set" current. As the light power is increased, the light power for which the photocurrent can equal the "set" current is passed. For higher light powers the constant current source will decrease the photoabsorption in order to maintain equality between the photocurrent and the "set" current. Therefore, the constant current source maintains a constant absorbed power in the MQW. The device thus operates as a linear inverting modulator in which the absorption is linear with the "set" current. The modulator is inverting because as the "set" current is increased the transmitted intensity is decreased in order to increase the absorbed power. In the limit of an ideal constant current source the curve **260** can become very steep in the vicinity of the set current value I_c **250**.

An exemplary constant current source using a transistor and suitable for practicing the invention is shown in FIG. **20**. A pin MQW diode strtsture modulator is connected in reverse bias configuration between contacts **270, 272**. Voltage source V_O provides a constant DC potential. As the photocurrent generated in the pin MQW diode structure attempts to change with changes in incident light intensity, the transistor will maintain the current constant and change the voltage between contacts **270, 272** accordingly. The pin MQW structure will then exhibit either bistability or linear inverting modulation as discussed hereinabove. Junction transistors and field effect transistors may equally well serve as a constant current source.

An exemplary embodiment of the invention having a photodiode as a constant current limiter is shown in FIG. **21**. The MQW modulator **281** is shown as the intrinsic layer of a pin diode **280**. The photodiode **282** is shown with an optional intrinsic layer **284**. The intrinsic layer **284** is optionally included so that the depletion region will remain approximately the same size independent of bias. Light absorption occurring within the depletion region generates the diode photocurrent, and with the size of the depletion region substantially independent of bias, the photocurrent will be substantially independent of bias and only dependent on the absorbed optical power. For a pin diode **280** and MQW modulator **281** having a bistable characteristic, the operating point is controlled by the optical power absorbed by the photodiode **282**. A first light beam **285** having a first spectral composition may be directed at photodiode **282** in order to control the constant current. A second light beam **287** having a second spectral composition may be controlled by pin diode **280** and MQW modulator **281**. In operation, the constant potential V_O set by potential source **286** appears partly across photodiode **282** and partly across pin diode **280**. The fraction of potential V_O across the two components **280, 282** changes as the requirement for constant current in photodiode **282**

requires. In the linear inverting modulator mode, an increase in intensity of the light beam absorbed by photodiode **282** causes an increase in current through the MQW modulator, and an increase in absorption of MQW layers **281**. Thus an increase in intensity in the control light beam causes a decrease in intensity of the light beam transmitted through the pin diode **280**, giving an decrease approximately linear with the increase in intensity of the control beam.

FIG. **22** shows an exemplary embodiment of the invention grown as an integrated photodiode **290** in electrical series with a pin diode MQW modulator **292**. Photodiode **290** and pin MQW diode **292** are both reverse biased. Junction **294** is a forward biased diode, and so photocurrent produced within photodiode **290** can pass into pin MQW diode **292**. Photodiode **290** is designed so that photocurrent is nearly independent of bias, and may include an intrinsic layer (not shown). A first light beam **296** is absorbed by photodiode **290** in order to make the constant "set" current. A second light beam **298** is transmitted by pin MQW diode **292** to become output light beam **300**. The semiconductor structure shown in FIG. **22** will work with the photodiode **290** operating independently of the pin MQW diode **292** as discussed above if the wavelength and absorption for first light beam **296** is chosen so that it does not penetrate and become absorbed in MQW **293**, and if second light beam **298** is not appreciably absorbed by photodiode **290**. If either light beam **296**, **298** is absorbed by both photodiode **290** and pin MQW diode **292**, then a more complicated interaction occurs. The entire structure may, for example, be grown by molecular beam epitaxy from a single family of materials such as GaAs, GaAlAs, and the appropriate n and p doping materials. The semiconductor layers shown in FIG. **22** may exhibit transistor action. In advertent transistor action is called "parasitic transistor action" and the involved layers are called parasitic transistors. Transistor action may be enhanced or inhibited by the choice of thickness of materials in order to control diffusion of charge carriers from one semiconductor layer to another layer.

For example the pin MQW diode **292** may be operated with light beams directed perpendicular to the layer planes, as shown in FIG. **7**, FIG. **8** or FIG. **22**. The p and n regions of photodiode **290** absorb energy from first light beam **296**, and they should be transparent at the wavelength of second light beam **298**. For the GaAs/GaAlAs system this transparency may be achieved by making the photodiode entirely out of GaAlAs with a bandgap chosen to be higher than the photon energy used in second light beam **298**. Also the use of superlattice material for photodiode **290** results in a higher bandgap for photodiode **290**. The photon energy of first light beam **296** would then be chosen higher than the photon energy for second light beam **298**. Similar techniques may be used for other material systems.

FIG. **23** shows an exemplary embodiment of an integrated photodiode and pin MQW diode structure. The layers may be grown by molecular beam epitaxy, a mesa etched, an insulating layer deposited, and a hole made in the insulator at the top of the mesa, and a conducting layer deposited so that it contacts the top layers of the mesa, much as discussed with reference to FIG. **9** and FIG. **10**. Also structures as shown in FIG. **23** are suitable for fabrication into arrays, as discussed with reference to FIG. **11**. An array of structures such as shown in FIG. **23** may be used to process numerous parallel light beams, and for other optical parallel processing. An array of structures as shown in FIG. **23** requires only two electrical connections for the array, as discussed above with reference to FIG. **11**.

In FIG. **24** an exemplary embodiment of the invention used as a spatial light modulator is shown. An array **310** of self electrooptic effect devices (SEED) as shown in FIG. **23** and FIG. **11**, is used. Illumination **312**, which may be incoherent and broadband, is directed toward an object **314**. A fraction of illumination **312** is reflected from object **314**, and is focused as light beam **315**, after filtering out of key wavelengths by filter **317**, onto an array **310** of SEED devices. Light source **316** illuminates array **310** of SEED devices. The transmission of each individual SEED device in array **310** depends upon the illumination intensity reflected by object **314**. The wavelength used by source **316** is filtered out of light beam **315** by filter **317**. Output beam **321** is formed by transmission of light from source **316** by SEED devices in array **310**. The transmission state of the SEED devices is determined by the intensity of that part of the image of object **314** focused upon each SEED device. Output beam **321** is first deflected by beamsplitter **324**, and then focused by a lens **322** to form an image **320**. If a high intensity illumination of a SEED device in an array **310** results in low transmission of the SEED device for light from source **316**, then the image **320** will be the negative of illuminated object **314**. Image **320** may be formed at a wavelength completely different from wavelengths contained in illumination **312**. For example, using GaAs/GaAlAs, SEED devices can use visible incoherent illumination **312**, and produce an infra-red image **320** using a coherent light source at source **316**.

FIG. **25** shows an exemplary embodiment of the invention having a phototransistor integrated into the MQW modulator structure. The device has only two electric connections. The base is not separately connected to any external electric circuit. The restriction of only two electrical contacts to a device was chosen so that an array of devices would not require more than just two electrical connections for the entire array, as discussed with reference to FIG. **11**.

FIG. **25** shows an exemplary embodiment of the invention having a pin diode MQW structure **330** integrated into a semiconductor body **332**, and also having a phototransistor **334** integrated into the semiconductor body **332**. Phototransistor **334** is in electrical series with the pin diode structure **330**. In operation, light is absorbed in the phototransistor and thereby produces a photocurrent. The photocurrent is amplified by transistor action among the emitter region **338**, the base region **336**, and the collector region **340**. The amplified photocurrent is a substantially constant current supply much as is the transistor shown in FIG. **20**, or the photodiode shown in FIG. **21**. An advantage of the phototransistor shown in FIG. **25** is that the photocurrent generated by light absorption is amplified, thereby making the device more sensitive to light than the simple photodiode structure of FIG. **21**. The phototransistor **334** functions as a constant current source and operates as described with reference to FIG. **16** through FIG. **19**.

The semiconductor structure shown in FIG. **22** may serve as a phototransistor, as well as serving as a photodiode as described above. In FIG. **22** the n doped layer **294A** serves as the base of a phototransistor, and the two p doped layers **294B**, **294C**, serve as emitter and

collector, respectively. The semiconductor structure of FIG. **22** serves as a photodiode if the n doped layer **294A** is made thick enough so that carriers cannot diffuse between layers **294B** and layer **294C**, or if some other means to prevent such carrier diffusion is used such as incorporating a tunneling junction as a carrier converter within layer **294A**. However layers **294A**, **294B**, and **294C** function as a phototransistor if the thickness of layer **294A** is chosen sufficiently thin so that a significant number of carriers can diffuse from layer **294B** to layer **294C**. Although a pnp transistor is shown as in FIG. **25**, an arrangement of a npn transistor will serve equally well as long as the pin MQW modulator is reverse biased. For example, in FIG. **25** each of the n layers may be replaced by a p layer, and each of the p layers may be replaced by an n layer, and the polarity of the supply voltage reversed.

When the semiconductor structure shown in FIG. **22** is constructed to function as a phototransistor it is a constant current source in series with the MQW modulator **293**, and functions as described with reference to FIG. **16** through FIG. **19**.

The integrated semiconductor structures shown in FIG. **22** and FIG. **25** are particularly well suited for fabrication into an array of individual devices much as is shown in FIG. **11**. No electrical connection need be made to the base region of the phototransistors, and so an array needs only two electrical connections. For example, the semiconductor structure of FIG. **25**, when incorporated into an array of similar devices, may have all of the device's layers **344** connected together electrically, and may have all of the device's layers **338** connected together electrically. The fabrication steps shown in FIG. **9** and FIG. **10** may be used to fabricate an array of devices as shown in FIG. **25**, with the addition of steps required to make the additional layers shown in FIG. **25**.

FIG. **26** shows an exemplary embodiment of the invention having a phototransistor and a MQW modulator coupled by having both structures respond to the same light beam. The configuration shown in FIG. **26** may be made by using separate discrete components, or may be made using an integrated semiconductor structure such as shown in FIG. **22** and FIG. **25**.

At least four separate cases of operation are possible using the embodiment of the invention shown in FIG. **26**. The four cases are made by choosing whether the light beam penetrates the phototransistor first or penetrates the MQW modulator first, and secondly whether the absorption of the modulator increases or decreases with increasing external voltage applied to the modulator.

In the first case, the light beam penetrates the phototransistor first as shown by beam **350**, and the absorption of the modulator increases with increasing voltage. Light beam **352** is the light output of the device. Operation of the device is analyzed by initially considering the light intensity to be very low and following the response of the device as the intensity is raised. At low intensity there is little photocurrent and most of the supply voltage is across the phototransistor. With increasing light intensity the photocurrent increases, the phototransistor current increases along with a decrease in emitter-collector voltage, and the voltage across the modulator increases. The modulator absorption increases with increasing modulator voltage, thereby reducing the intensity of the output light beam **352**. The light output power plotted versus the light input power will therefore rise and then fall as the modulator absorption increases. By adjusting the operating point to be within the range wherein light output power decreases with increasing light input power the device can be used as an inverting amplifier.

In the second case the light beam penetrates the transistor first as light beam **350**, however the absorption of the modulator decreases with increasing voltage. At low intensity there is very little photocurrent, most of the supply voltage is across the phototransistor, and consequently the modulator is very absorbing because the voltage across it is low. Output light beam **352** is therefore substantially blocked by the MQW modulator. As the intensity of beam **350** is increased the voltage across the MQW modulator increases, and the modulator becomes less absorbing, and the intensity of output light beam **352** rises rapidly.

For the third case the light beam penetrates the MQW modulator first and the phototransistor second, as shown by light beam **360**, and the MQW absorption increases with increasing voltage. Light beam **360** is the input light beam, and light beam **362** is the output light beam. At low intensity the supply voltage is across the phototransistor and the MQW modulator is substantially transparent. As the intensity increases the phototransistor begins to conduct, causing the voltage across the MQW modulator to increase, and the modulator becomes more absorbing thereby blocking the light from reaching the phototransistor. With a proper choice of operating characteristics, the device will reach a constant transmitted power. In this case the invention serves as a light limiter.

For the fourth case the light penetrates the MQW modulator first as light beam **360**, and the MQW modulator absorption decreases with increasing applied voltage. At very low intensity most of the supply voltage is across the phototransistor. Therefore the modulator is substantially opaque and little light penetrates to the phototransistor. However, as the light intensity is raised power begins to reach the phototransistor, the voltage across the phototransistor begins to drop, and the voltage across the MQW modulator begins to rise. The MQW modulator becomes increasingly transparent with increasing voltage. The phototransistor then sees a rapidly rising light intensity, leading to a rapidly rising light output power as the light input power is further increased.

Devices with additional characteristics may be made by illuminating either the phototransistor or the MQW modulator with additional beams of light (not shown). The operating point is adjusted by using the intensity of a light beam as the control element.

An exemplary embodiment of the invention in which the optical path length changes in response to light beam intensity is shown in FIG. **27**. A modulator made with low refractive index p and n contact layers **400** and **402** around an intrinsically doped MQW layer **404** of higher refractive index than layers **400** and **402** serves as a modulator and an optical waveguide. Light beam **410** incident on photodiode **406** will generate a photocurrent which will cause the voltage over the MQW region **404** to change, thereby changing its absorption spectrum and its refractive index spectrum. If incident light beam **412** is chosen so that it is in a spectral region where the change in refractive index is significant, such as would be found for photon energies close to but lower than the exemplary operating point **147** in FIG. **6**, then the optical path length seen by beam **412** on pass-

ing through the structure will be changed significantly. This property may be exploited to make optically controlled resonators, interferometers, directional couplers and other devices sensitive to optical path length. If the control light beam **410** is derived from the light beam **412** before, after or during its passage through the structure, devices may be made employing internal feedback, enabling the beam **412** to affect its own optical path length in a nonlinear manner.

Alternative structures may be made using phototransistors or other light sensitive materials and photodiodes and phototransistors may be integrated into the structure as described in FIG. **22** and FIG. **25** except the direction of the light beams may be different from that shown in FIGS. **22** and **25**. Using the structures in FIG. **22** and **25**, the fringe field of the optical mode in the waveguide may be partially absorbed in the phototransistor or photodiode, thereby deriving the control beam from the incident light beam during the passage of the incident beam **412** through the structure.

A photoconductor may be used rather than a photodiode or phototransistor as shown in FIG. **21**, FIG. **22**, FIG. **23**, FIG. **25**, or FIG. **27**, for controlling the optical absorption of the MQW structure.

Materials for making the MQW structures may include ternarys or quarternaries such as InGaAlAs, InGaAsP, InGaAs, InAl, As, and other semiconductor materials such as InP. For example alloys or compounds made of Group III–V elements and Group II–VI elements are particularly useful in making MQW structures.

What is claimed is:

1. An optical device comprising:

means responsive to light for generating a photocurrent; wherein the improvement comprises;

a structure having a semiconductor quantum well region; and

means responsive to said photocurrent for electrically controlling an optical absorption of said semiconductor quantum well region in order to cause said optical absorption of said semiconductor quantum well region to vary in response to variations in said photocurrent.

2. An optical device as in claim **1**

wherein said means responsive to light for generating a photocurrent is said semiconductor quantum well region.

3. An optical device as in claim **1**

wherein said means responsive to said photocurrent is a resistor.

4. An optical device as in claim **1** wherein said structure having a semiconductor quantum well region has one semiconductor quantum well layer.

5. An optical device as in claim **1**

wherein said structure having a semiconductor quantum well region has a plurality of semiconductor quantum well layers.

6. An optical device as in claim **1**

wherein said means responsive to said photocurrent applies a voltage substantially perpendicular to a layer plane of said quantum well regions.

7. An optical device as in claim **1**

wherein said means responsive to said photocurrent applies a voltage substantially parallel to a layer plane of said quantum well region.

8. An optical device as in claim **1**

further comprising means for directing a beam of light substantially perpendicular to a layer plane of said quantum well region.

9. An optical device as in claim **1**

further comprising means for directing a beam of light substantially parallel to a layer plane of said quantum well region.

10. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a source of electric potential.

11. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a resistor being made an integral part of said structure having a semiconductor quantum well region.

12. An optical device as in claim **1** further comprising an array of said optical devices.

13. An optical device as in claim **1**

further comprising a two dimensional array of said optical devices wherein each said optical device is capable of performing logic indepenent of each of said other optical devices within said array.

14. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises semiconductor regions forming a photodiode and made an integral part of said structure having a semiconductor quantum well region.

15. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises semiconductor regions forming a transistor and made an integral part of said structure having a semiconductor quantum well region.

16. An optical device as in claim **1**

wherein said structure having a semiconductor quantum well region further comprises a p doped semiconductor layer and an n doped semiconductor layer wherein said quantum well region is electrically attached on a first side to said p doped semiconductor layer and said quantum well region is electrically attached on a second side to said n doped semiconductor layer.

17. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises an inductor.

18. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a constant current source.

19. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a transistor.

20. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a phototransistor.

21. An optical device as in claim **1**

wherein said means responsive to said photocurrent further comprises a photodiode.

22. An optical device as in claim **1**

further comprising means for directing light into said means responsive to light for generating a photocurrent from which means responsive to light said light emerges and enters said semiconductor quantum well region.

23. An optical device as in claim **1**

further comprising means for directing light into said semiconductor quantum well region from which region it emerges and enters said means responsive to light for generating a photocurrent.

24. An optical device as in claim 1 wherein said means responsive to light for generating a photocurrent is a phototransistor.

25. An optical device as in claim 1 wherein said means responsive to light for generating a photocurrent is a photodiode.

26. An optical device as in claim 1 wherein said means responsive to light for generating a photocurrent is a photoconductor.

27. An optical device comprising:

means responsive to light for generating a photocurrent; wherein the improvement comprises;

a structure having a semiconductor quantum well region; and

means responsive to said photocurrent for electrically controlling an index of refraction of said semiconductor quantum well region in order to cause said index of refraction of said semiconductor quantum well region to vary in response to variations in said photocurrent.

28. An optical device as in claim 27 wherein said means responsive to light for generating a photocurrent includes said semiconductor quantum well region.

29. An optical device as in claim 27 wherein said means responsive to said photocurrent includes a resistor.

30. An optical device as in claim 27 wherein said structure having a semiconductor quantum well region includes one semiconductor quantum well layer.

31. An optical device as in claim 27 wherein said structure having a semiconductor quantum well region includes a plurality of semiconductor quantum well layers.

32. An optical device as in claim 27 wherein said means responsive to said photocurrent applies a voltage substantially perpendicular to a layer plane of said quantum well region.

33. An optical device as in claim 27 wherein said means responsive to said photocurrent applies a voltage substantially parallel to a layer plane of said quantum well region.

34. An optical device as in claim 27 further comprising means for directing a beam of light substantially perpendicular to a layer plane of said quantum well region.

35. An optical device as in claim 27 further comprising means for directing a beam of light substantially parallel to a layer plane of said quantum well region.

36. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a source of electric potential.

37. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a resistor being made an integral part of said structure having a semiconductor quantum well region.

38. An optical device as in claim 27 further comprising an array of said optical devices.

39. An optical device as in claim 27 further comprising a two dimensional array of said optical devices wherein each said optical device is capable of performing logic independent of each of said other optical devices within said array.

40. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises semiconductor regions forming a photodiode and made an integral part of said structure having a semiconductor quantum well region.

41. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises semiconductor regions forming a transistor and made an integral part of said structure having a semiconductor quantum well region.

42. An optical device as in claim 27 wherein said structure having a semiconductor quantum well region further comprises a p doped semiconductor layer and an n doped semiconductor layer wherein said quantum well region is electrically attached on a first side to said p doped semiconductor layer and said quantum well region is electrically attached on a second side to said n doped semiconductor layer.

43. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises an inductor.

44. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a constant current source.

45. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a transistor.

46. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a phototransistor.

47. An optical device as in claim 27 wherein said means responsive to said photocurrent further comprises a photodiode.

48. An optical device as in claim 27 further comprising means for directing light into said means responsive to light for generating a photocurrent from which means responsive to light said light emerges and enters said semiconductor quantum well region.

49. An optical device as in claim 27 further comprising means for directing light into said semiconductor quantum well region from which region it emerges and enters said means responsive to light for generating a photocurrent.

50. An optical device as in claim 27 wherein said means responsive to light for generating a photocurrent includes a phototransistor.

51. An optical device as in claim 27 wherein said means responsive to light for generating a photocurrent includes a photodiode.

52. An optical device as in claim 27 wherein said means responsive to light for generating a photocurrent includes a photoconductor.

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