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[54] **PHOTOVOLTAIC DRIVEN MULTIPLE QUANTUM WELL OPTICAL MODULATOR**

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Related U.S. Application Data

[60] Continuation-in-part of Ser. No. 149,653, Jan. 28, 1988, Pat. No. 4,818,079, which is a division of Ser. No. 3,633, Jan. 15, 1987, abandoned.

[51] Int. Cl.^{5} G02F 1/01
[52] U.S. Cl. 350/354
[58] Field of Search 350/354, 355, 356; 357/4

[56] **References Cited**

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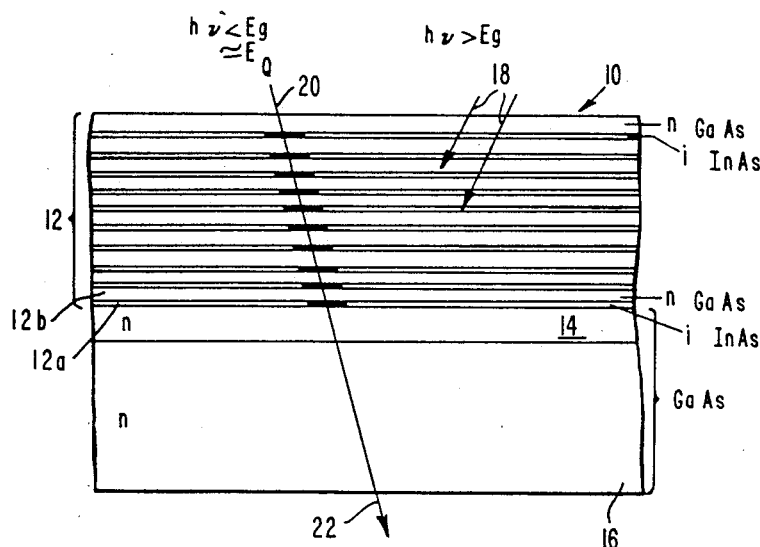|			
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[57] **ABSTRACT**

Multiple quantum well (MQW) structures (12) are utilized to provide real-time, reliable, high-performance, optically-addressed spatial-light modulators (SLM) (10). The optically-addressed SLM comprises a vertical stack of quantum well layers (12a) within the penetration depth of an optical write signal 18, a plurality of space charge barriers (12b) having predetermined tunneling times by control of doping and thickness. The material comprising the quantum well layers has a lower bandgap than that of the space charge barrier layers. The write signal modulates a read signal (20). The modulation sensitivity of the device is high and no external voltage source is required. In a preferred embodiment, the SLM having interleaved doped semiconductor layers for driving the MQW photovoltaically is characterized by the use of a shift analogous to the Moss-Burnstein shift caused by the filling of two-dimensional states in the multiple quantum wells, thus allowing high modulation sensitivity in very narrow wells. Arrays (30) may be formed with a plurality of the modulators.
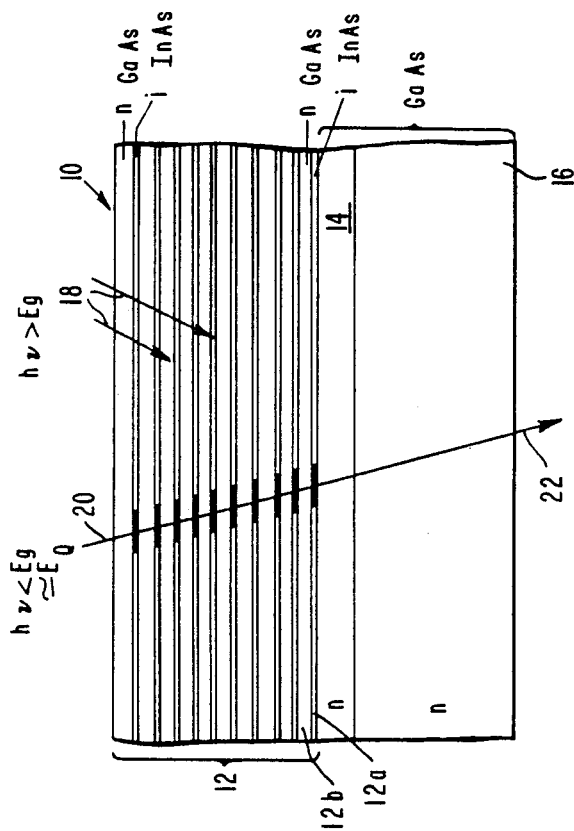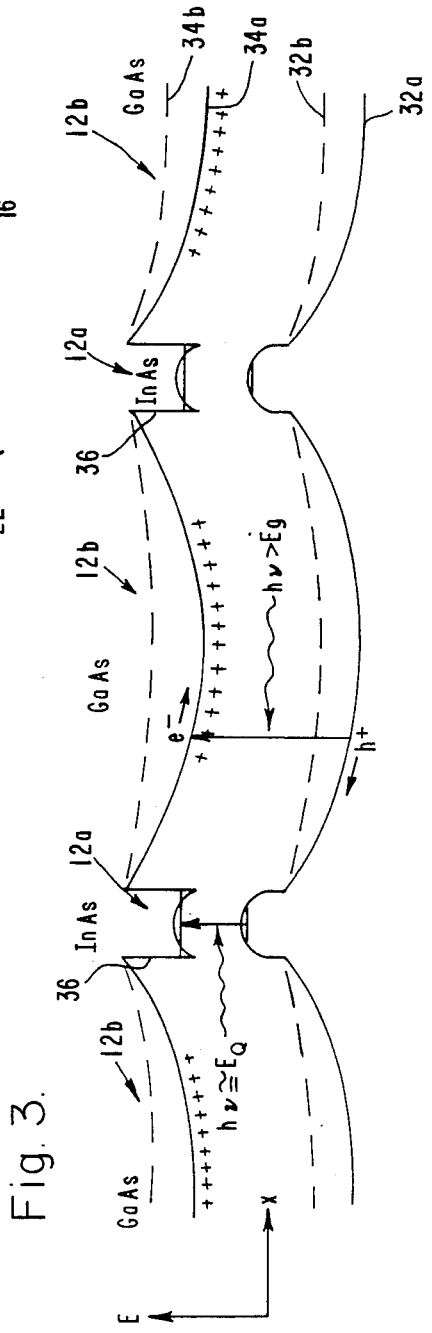
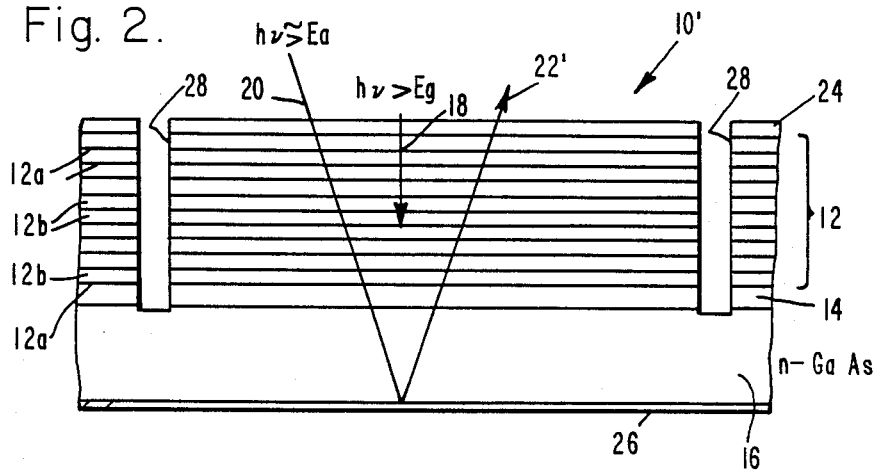**18 Claims, 3 Drawing Sheets**

Fig. 1.

Fig. 3.

Fig. 2.

$h\nu \gtrsim E_a$

$h\nu > E_g$

10'

28   20   18   22'   28   24

12a

12b

12b

12a

12

14

n– Ga As

26   16

Fig. 4.

E

12b   36   12a ΔE e⁻   12b

++   ++

$h\nu$ E_Q 18

x   20 $h\nu$

(In,Ga) As   h⁺

Ga As   Ga As

42

30   18

20   22'

40   28
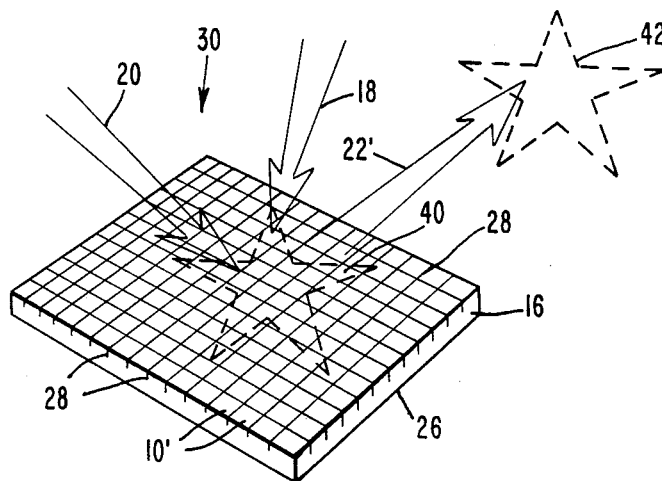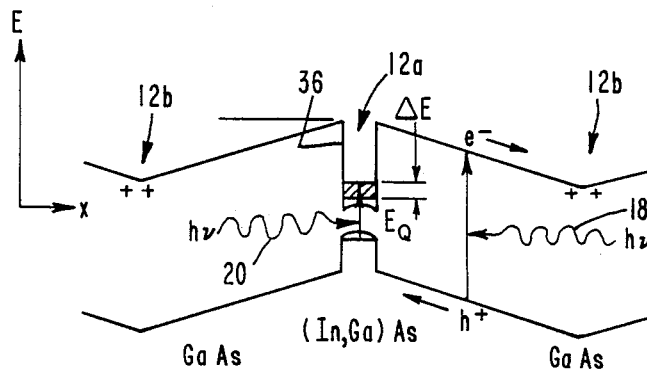
28

16

28   26

10'

Fig. 7.

Fig. 5.

Fig. 6.

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PHOTOVOLTAIC DRIVEN MULTIPLE QUANTUM WELL OPTICAL MODULATOR

ORIGIN OF INVENTION

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

CROSS REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part application of Ser. No. 07/149,653, now U.S. Pat. No. 4,818,079, filed Jan. 28, 1988, which is a divisional application of Ser. No. 07/003,633, now abandoned, filed Jan. 15, 1987.

TECHNICAL FIELD

The present application relates to semiconductor modulators, and, in particular, to semiconductor modulators employing multiple quantum wells.

BACKGROUND ART

The formation of ultrathin layers of different semiconductor materials (heterostructures) on the order of 50 to 200 Å leads to the quantization of confined carriers. Such ultrathin heterostructures can form quantum well structures and be repeated into alternating layers forming multiple quantum wells and superlattices.

The energy band diagram for such structures evidences abrupt steps in the energy gap which form potential wells in the conduction and valence bands, as is well-known. Appropriate selection of materials, compositions and layer thicknesses permits fabrication of unique electro-optic devices.

The use of optics to perform signal processing is attractive because of the high speed of light and the opportunity of using many parallel channels, which yield the promise of very high throughput rates. However, a major obstacle to the realization of this goal has been the lack of a real-time, reliable, high performance spatial-light-modulator (SLM). This lack is largely due to the limitations of materials.

DISCLOSURE OF INVENTION

In accordance with the invention, multiple quantum well (MQW) structures are utilized to provide real-time, reliable, high performance, optically-addressed spatial-light-modulators (SLM). Such MQW structures comprise alternating layers of a first material (quantum well) material alternating with a second material (space charge barrier), the bandgap of the quantum well material being lower than that of the barrier material. Examples of suitable lower bandgap/higher bandgap materials systems include such III-V systems as InAs/GaAs, (In,Ga)As/GaAs, InAs/AlSb, (In,Ga)As/(Al,Ga)As, (In,Ga)As/InP, and (In,Ga)As/(In,Al)As.

The optically-addressed SLM comprises a vertical stack of MQW layers within the penetration depth of an optical write signal and with each quantum well separated by a space charge barrier (in the larger bandgap material) having predetermined tunneling relaxation times by control of doping and thickness, whereby modulation sensitivity is high and no external voltage source is required. An incident optical read signal may be modulated by an incident optical write signal.

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In a preferred embodiment, an improved real-time, reliable, high-performance spatial-light modulator having interleaved space charge barriers formed by doped semiconductor layers for driving the multiple quantum wells photovoltaically, is characterized by the use of the shift caused by either the quantum confined Stark effect, possibly enhanced by strain effects, or by filling of two-dimensional states in the multiple quantum wells. The shift of absorption edge due to the filling of states is analogous to the well-known Moss-Burnstein shift in bulk materials but is much larger because of the carrier confinement and the low density of two-dimensional quantum well states.

In additional embodiments, p-n junctions or n-i-p-i structures may be employed to overcome smaller band offsets, in which the quantum wells are formed either between n-layers for the quantum state filling effect or in the intrinsic region for the quantum confined Stark effect.

Thus, the selection of appropriate materials, having the properties specified above, permit fabrication of high performance, optically-addressed SLMs.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a photovoltaic-driven multiple quantum well modulator in accordance with an embodiment of the invention;

FIG. 2 is a view similar to that of FIG. 1, illustrating an alternate embodiment of the invention;

FIG. 3, on coordinates of length (x) and energy (E), is a plot depicting the energy diagram through five layers of the structure depicted in FIG. 1 and illustrating the quantum-confined Stark effect in conjunction with selective doping;

FIG. 4 is a plot similar to that of FIG. 3, but depicting the energy diagram resulting from use of quantum state filling in conjunction with delta doping;

FIG. 5 is a plot similar to FIGS. 3 and 4, depicting yet another embodiment of the invention, employing p-n junctions to overcome smaller band offsets used in conjunction with quantum wells and quantum state filling;

FIG. 6 is a plot similar to FIGS. 3-5 depicting another embodiment employing n-i-p-i structures to overcome smaller band offsets, used in conjunction with MQWs and quantum confined Stark effect; and

FIG. 7 is a perspective view of a large array spatial light modulator in accordance with the invention.

BEST MODES FOR CARRYING OUT THE INVENTION

Recent advances in molecular-beam-epitaxy (MBE) have made possible the growth of new semiconductor microstructures such as multiple quantum wells (MQWs) and compositional superlattices. This has enabled the opportunity of engineering the material structure with specifically enhanced electro-optic properties.

In accordance with the invention, a novel real-time, high performance, optically-addressed SLM comprises a vertical stack of multiple quantum well layers within the penetration depth of an optical write signal, a plurality of space charge barriers having predetermined tunneling relaxation times by control of doping and thickness, whereby modulation sensitivity is high and no external electrical contacts or voltage source is required.

FIGS. 1 and 2 are cross-sectional views of the SLM of the invention, and FIG. 3 is an energy diagram of a portion of the structure shown in FIGS. 1 and 2.

Shown in FIG. 1 is a photovoltaic-driven MQW modulator **10** comprising a structure **12** of a plurality of alternating layers of two dissimilar semiconductor materials, one comprising the quantum well **12a** and the other providing space charge barriers **12b**. The quantum well material must have a significant conduction band offset relative to the adjacent material (such as shown in FIG. 3) so that the space charge barrier is effective and electron recombination is not too fast.

The MQW structure **12** is formed on a buffer layer **14** comprising n-GaAs, which in turn is formed on a GaAs substrate **16**, doped with an n-type dopant (see FIGS. 1 and 2). The substrate doping should not be important, but some doping may be necessary to provide a ground plane or equipotential plane to drain off charge accumulation through the substrate and avoid hysteresis effects. The MQW structure **12** begins with an undoped InAs layer **12a** on layer **14** and ends with an n-GaAs layer **12b**.

The InAs/GaAs structure **12** permits a write signal **18** to be absorbed therein at photon energies greater than the GaAs bandgap E_g. A read signal **20** would be at energies below E_g, but close to the quantum level E_Q, and thus could be transmitted through the GaAs substrate **16**, without requiring removal of the substrate by etching, to provide an output signal **22**.

FIG. 2 shows another modulator **10'**, similar to that depicted in FIG. 1, and illustrates the addition of a transparent anti-reflective coating **24** over the multiple quantum well structure **12** on the front surface, a metal reflective layer **26** on the rear surface of the substrate **16**, and etched grooves **28** used in forming an array **30**, shown in FIG. 7. The preferred added anti-reflection coating **24** and reflective metal layer **26** at the back side of the wafer **16** would provide two passes of the read signal **20**, and thus would double the modulation depth, providing a reflected modulated output signal **22'**. Alternatively, the device could be made into an etalon structure, for multiple passes of the read signal, for further enhancement of the modulation depth.

In a particular embodiment (shown in FIG. 3), the structure **12** comprises alternating layers of undoped InAs (quantum well layer) **12a** and selectively-doped n-GaAs (providing the space charge barrier) **12b**. In this system, the quantum well material, InAs in this example, has a lower bandgap than the GaAs substrate material. This property provides for quantum well energies below the bandgap of the GaAs substrate, allowing light that can be modulated by the quantum wells to pass freely through the substrate. Examples of other lower bandgap/higher bandgap systems include (In,-Ga)As/GaAs, InAs/AlSb, (In,Ga)As/(Al,Ga)As (In,-Ga)As/InP, and (In,Ga)As/(In,Al)As. It should be noted that the use of the term "undoped" herein means unintentionally doped, since all semiconductor materials include impurities to some extent.

In this example, the undoped InAs layers **12a** must be very thin, on the order of about 50 Å, to stay within the elastic limit of strain and minimize formation of misfit dislocations (defects). However, since the thickness of this layer **12a** affects performance, a less strained system, such as (In,Ga)As/GaAs or InAs/AlSb, or an unstrained system, such as (In,Ga)As/InP, might be better alternative materials systems. Such other III-V materials, not so strained, will permit fabrication of layers greater than about 100 Å in thickness, which are preferred for this embodiment which utilizes the quantum confined Stark effect. On the other hand, it may

also be desirable to take advantage of strain (within the elastic limit), since it is predicted to create enhanced electro-optical properties with (111) orientation.

The alternating n-GaAs layers **12b** are thicker, on the order of about 300 to 500 Å. The sheet doping N_s is on the order of about 1 to 4×10^{12} cm^{-2}. The n-doping should not be so large as to fill the states in the quantum well (with electrons) to the next quantum level. The doping need only be sufficient to satisfY the requirement of the space charge barrier; that is, by Gauss' law, the minimum dopant sheet density N_s is given by

$$N_s \gtrsim (\epsilon/e^2)(\Delta E_c/d)$$

where ϵ is the semiconductor permittivity, e is the electron charge, ΔE_c is the conduction band offset, and d is the barrier thickness.

Preferably, a selectively-doped profile is employed across the thickness of each layer **12b**, most preferably undoped at the boundaries and doped in the center thereof. If such selective doping is employed, the extent of doping may in the limit be on the order of about 10^{19} cm^{-3} over some 10 Å, giving N_s on the order of 10^{12} cm^{-2}, according to a recently developed technique of MBE referred to as delta doping. In this case, the thickness of the layer **12b** may be reduced to about 200 to 300 Å. Such a decrease in thickness for layers **12b** permits stacking of more alternating layers **12a**, **12b**, which results in a desirable increase in the number of active (absorbing) quantum wells provided by layer **12a**. It should be noted that the stacking of the MQWs **12a** should be within the penetration depth of the optical write signal **18** of about 1 to 2 μm.

Layer **14** is about 1,000 Å thick, which includes a buffer layer to the substrate, and is selectively doped adjacent the first InAs layer **12a** to the same extent as the n-layers **12b**. The underlying substrate region may be uniformly n-doped, for example, anywhere in the range of about 10^{15} to 10^{18} cm^{-3}.

A p-doped substrate **16**, p-doped buffer layer **14** and p-doped layers **12b** may alternatively be employed, especially of the offset of the valence bands is larger than that of the conduction bands, such as is the case for the material system (In,Ga)As/InP.

The electron-hole pairs generated by the write signal **18** are separated by the built-in space charge field. As indicated in FIG. 3, this charge separation changes the barrier profiles from **32a** and **34a** (in the absence of light) to **32b** and **34b** (with light on). This photovoltaic effect produces a very large field change at the boundaries of the quantum wells **12a**, which leads to large shifts of the absorption edge energy E_Q by the quantum confined Stark effect. As the write signal **18** shifts the absorption edge E_Q through the photon energy of the read signal **20**, it produces the modulated output signal **22**.

The symmetric form of the field at the quantum well boundaries **36** requires larger fields and quantum well thicknesses to produce the same shift as in the case of the more usual unidirectional fields. However, much higher fields (well in excess of 10^5 V/cm) may be easily employed, since the fields are internally generated and thus no avalanche breakdown is possible.

The integration/relaxation time of the system is determined at lower operating temperatures by tunneling through the n-doped space charge barriers **34**, which can be predetermined by choice of doping distribution and layer thickness. For example, at a given layer **12b**

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thickness, the barrier tunneling time can be increased (to achieve longer integration times) by concentrating the dopant near the middle of the layers, in the preferred doping profile described above.

A major advantage of using the quantum confined Stark effect in the embodiment described above is when strain enhancement effects are to be utilized. In another embodiment, when strain is not utilized, the sensitivity of the device described above can be increased by employing the shift due to the filling of two-dimensional states in the quantum wells, as shown in FIG. 4. This approach is termed the "quantum state filling effect". In this case, quantum well materials are preferred which have low effective mass ($m^* = 0.023 \times$ free electron mass), such as InAs. Thinner quantum wells, about 50 Å, may be used, which are within the elastic limit of InAs/GaAs.

The low effective mass of InAs, m^*, gives a low density of two-dimensional (2D) electron states, and a corresponding large shift in the absorption edge E_Q given by:

$$\Delta E = (\pi \hbar^2 / m^*) n_s,$$

where $\hbar$ is Planck's constant divided by 2π and n_s is the electron density per unit area of occupied 2D states. The density n_s is related to the field, F_s, at the boundaries of the quantum well through Gauss' law, by

$$F_s = e n_s / \epsilon.$$

As described above, the photovoltaic effect from the write signal produces a decrease of F_s and thus from above an equivalent decrease of n_s, leading to a corresponding decrease in V and shift in E_Q.

The interleaved n-doped GaAs layers 12b provide both the electrons in the quantum wells and the space charge barriers which separate hole-electron pairs generated by an optical write signal with $h\nu > E_g$ (GaAs). The photogenerated holes drift to the quantum wells 12a and recombine there with electrons in the wells, depleting their density n_s by an amount Δn_s, depending on the photon flux. Again, the decrease in occupied levels ΔE shifts the quantum well absorption edge E_Q. As indicated above for the structures depicted in FIGS. 1 and 2, the read signal 20, with photon energy just below the initial absorption edge, is modulated by the shift. The shift using InAs MQWs is expected to be about ten times larger than that using the quantum-confined-Stark effect in, for example, (Al,Ga)As/GaAs MQW structures driven by the same field (or equivalent charge).

It is noted that FIG. 3 utilizes distributed doping of the space charge barriers 12b, while FIG. 4 utilizes delta doping of the space charge barriers. The doping profile is not peculiar to either effect; however, the delta doping profile is preferably employed in either effect. Also, the dopant sheet density N_s is specified similarly for both effects.

Both of the foregoing effects require a conduction (or valance) band offset between the two materials of about 0.5 eV or more. This value is not easy to achieve with most common III-V materials, although it is greatly exceeded with the InAs/AlSb system (1.0 eV). To use materials systems with smaller conduction (or valance) band offsets, n-p junctions or "n-i-p-i" structures may be utilized.

FIG. 5 shows an energy diagram of an element of the embodiment employing p-n junctions in combination

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with quantum wells, which uses the quantum state filling effect. As above, the write signal with photon energy greater than the GaAs bandgap generates electron-hole pairs which are separated by the internal field produced, in this case, by the p-n junctions (photovoltaic effect). The photoelectrons fill the quantum states by an amount E, causing a shift in the absorption edge which modulates the read signal in the range of this shift. The p-n junction in FIG. 5 is seen to increase the total barrier separating the electrons and holes compared with the space charge barrier of FIG. 4, and thus increase the recombination time sufficiently for sensitive operation at room temperature. This structure is incorporated into the same overall modulator embodiment shown in FIGS. 1 and 2 with the additional p-GaAs layer.

FIG. 6 shows an energy diagram of an element of the embodiment which combines n-i-p-i structures with MQWs. In this case, the MQWs are placed in the uniform field of the intrinsic (i) region of the n-i-p-i structures and make use of the quantum confined Stark effect. In contrast to FIG. 3, this embodiment uses a unidirectional field. As in that case, the field is reduced by the photovoltaic effect of the write signal which causes the quantum confined Stark shift of the absorption edge, which in turn modulates the read signal. Again, the barrier produced by the n-i-p-i structure in FIG. 6 is much larger than the space charge barrier of FIG. 3, increasing the recombination time and sensitivity. However, this increase in recombination time and sensitivity also slows the response time, so that the optimum choice in barrier design will depend on the application. This is the well-known constant gain bandwidth product. As in the above cases, this structure is incorporated into the embodiments of FIGS. 1 and 2.

A large array spatial light modulator 30 could be fabricated straight-forwardly merely by etching sets of grooves 28 in a grid pattern, to separate pixels 10' of desired size, for example, into 10 m square, as illustrated in FIG. 7. An image 40 written in the MQW structure 12 by the write signal 18 is generated to form an output image 42 by modulation of the read signal 20 by the write signal 18, which produces the reflected signal 22' carrying the output image.

INDUSTRIAL APPLICABILITY

The various embodiments of the optically-addressed spatial-light-modulators described herein will find use in a variety of optical information processing applications.

Thus, optically-addressed spatial-light-modulators have been disclosed in a III-V semiconductor material which employ multiple quantum wells comprising alternating layers of a lower bandgap material (quantum well) and a higher bandgap material (space charge barrier). It will be apparent to one of ordinary skill in the art that various changes and modifications may be made without departing from the spirit and scope of the invention, and all such changes and modifications are intended to fall within the scope of the invention, as defined by the appended claims.

What is claimed is:

1. An internally photovoltaically driven optical modulator comprising a multiple quantum well structure formed on a substrate layer of a first material, said multiple quantum well structure comprising a plurality of alternating layers of said first material and a second

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material, said first material having a bandgap greater than that of said second material, said layers of said first material each comprising a doped semiconductor provided with a selectively-doped profile across the thickness of each layer thereof and forming a plurality of space charge barriers having predetermined tunneling times by control of doping and thickness thereof and said second material comprising an undoped semiconductor.

2. The optical modulator of claim 1 wherein said selectively-doped profile comprises doping in the center of each said layer and non-doping near the boundaries between said layer of said first material and said layer of said second material.

3. The optical modulator of claim 1 wherein said layers of said first material each constitute a space charge barrier comprising a layer of gallium arsenide and said layers of said second material each constitute a quantum well structure comprising layers of indium arsenide.

4. The optical modulator of claim 3 wherein said space charge barrier layers comprise n-GaAs about 200 to 500 Å thick and said quantum well layers comprise undoped InAs about 50 Å thick.

5. The optical modulator of claim 1 wherein said space charge barrier and said quantum well layers comprise combinations selected from the group consisting of gallium arsenide/indium arsenide, gallium arsenide/indium gallium arsenide alloy, aluminum antimonide/indium arsenide, aluminum gallium arsenide alloy/indium gallium arsenide alloy, indium phosphide/indium gallium arsenide alloy, and indium aluminum arsenide alloy/indium gallium arsenide alloy.

6. The optical modulator of claim 1 further provided with a reflective metal coating on said substrate layer opposite said multiple quantum well structure and further provided with an anti-reflective coating over said multiple quantum well structure.

7. The optical modulator of claim 1 wherein p-n junctions are formed within each space charge barrier layer.

8. The optical modulator of claim 7 wherein each space charge barrier layer comprises a triad of n-p-n layers, with each space charge barrier layer separated by said undoped (intrinsic) quantum well layer.

9. The optical modulator of claim 1 wherein each space charge layer is alternately doped n and p so as to form an n-i-p-i structure in conjunction with said undoped (intrinsic) quantum well layers.

10. An array of spatial light modulators comprising a plurality of internally photovoltaically driven optical modulators, separated from each other but sharing a common substrate, said optical modulators comprising

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a multiple quantum well structure formed on a substrate layer of a first material, said multiple quantum well structure comprising a plurality of alternating layers of said first material and a second material, said first material having a bandgap greater than that of said second material, said layers of said first material each comprising a doped semiconductor provided with a selectively-doped profile across the thickness of each layer thereof and forming a plurality of space charge barriers having predetermined tunneling times by control of doping and thickness thereof and said second material comprising an undoped semiconductor.

11. The array of claim 3 wherein said selectively-doped profile comprises doping in the center of each said layer and non-doping near the boundaries between said layer of said first material and said layer of said second material.

12. The array of claim 10 wherein said layers of said first material each constitute a space charge barrier comprising a layer of gallium arsenide and said layers of said second material each constitute a quantum well structure comprising layers of indium arsenide.

13. The array of claim 12 wherein said space charge barrier layers comprise n-GaAs about 200 to 500 Å thick and said quantum well layers comprise undoped InAs about 50 Å thick.

14. The array of claim 10 wherein said space charge barrier and said quantum well layers comprise combinations selected from the group consisting of gallium arsenide/indium arsenide, gallium arsenide/indium gallium arsenide alloy, aluminum antimonide/indium arsenide, aluminum gallium arsenide alloy/indium gallium arsenide alloy, indium phosphide/indium gallium arsenide alloy, and indium aluminum arsenide alloy/indium gallium arsenide alloy.

15. The array of claim 10 further provided with a reflective metal coating on said substrate layer opposite said multiple quantum well structure and further provided with an anti-reflective coating over said multiple quantum well structure.

16. The array of claim 10 wherein p-n junctions are formed within each space charge barrier layer.

17. The array of claim 16 wherein each space charge barrier layer comprises a triad of n-p-n layers, with each space charge barrier layer separated by said undoped (intrinsic) quantum well layer.

18. The array of claim 10 wherein each space charge layer is alternately doped n and p so as to form an n-i-p-i structure in conjunction with said undoped (intrinsic) quantum well layers.

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