LONG WAVELENGTH INFRARED DETECTOR

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Related U.S. Application Data

Continuation of Ser. No. 283,443, Dec. 12, 1988, abandoned.

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ABSTRACT

Long wavelength infrared detection is achieved by a detector made with layers of quantum well material bounded on each side by barrier material to form paired quantum wells, each quantum well having a single energy level. The width and depth of the paired quantum wells, and the spacing therefore, are selected to split the single energy level with an upper energy level near the top of the energy wells. The spacing is selected for splitting the single energy level into two energy levels with a difference between levels sufficient for detection of infrared radiation of a desired wavelength.

7 Claims, 2 Drawing Sheets
FIG. 1

IR Radiation

Contact

n⁺AlₓGa₁₋ₓAs

GaAs

AlₓGa₁₋ₓAs

GaAs

AlₓGa₁₋ₓAs

GaAs

AlₓGa₁₋ₓAs

GaAs

AlₓGa₁₋ₓAs

GaAs

Contact

FIG. 2

FIG. 3

(PRIOR ART)
LONG WAVELENGTH INFRARED DETECTOR

ORIGIN OF THE 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 USC 202) in which the Contractor has elected not to retain title.

This application is a continuation of application Ser. No. 07/283,443, filed Dec. 12, 1988, now abandoned.

TECHNICAL FIELD

The invention relates to infrared (IR) detectors using III-V compound semiconductors, such as gallium arsenide/aluminum arsenide, or any other combination of materials that exhibit quantum confinement effects, such as silicon/cobalt disilicide or silicon-germanium alloys, and more particularly to a method of making, and structure for, detectors using intersubband absorption in coupled quantum wells to achieve long wavelength IR detection in the range of about 10 μm to 100 μm.

BACKGROUND ART

There is a major need in space and military applications for infrared detectors. A great deal of research has focused on the possibility of using II-VI compounds, such as HgCdTe, to fabricate intrinsic semiconductor long wavelength IR detectors. The interest in these materials is motivated by the fact that the alloy changes from semiconducting to semimetallic as a function of composition. Thus, the bandgap, which is determined by the alloy composition, is narrow and can be reduced to zero for appropriate alloy compositions. However, current attempts to achieve IR detection with II-VI compounds have materials problems inherent in their chemistry, as well as immature growth and processing technologies.

The use of III-V compound semiconductors or other material systems would be preferable in view of the more mature growth and processing technologies available, as well as superior materials properties inherent in their chemistry, but IR detection in these materials has only been demonstrated in Al,Ga,As bounded by barrier layers of AlGaAs and GaAs. This invention of coupling quantum wells having single energy level, E,, and barrier material between the wells, such as GaAs, is useful in the principle of the present invention of improving absorption, i.e., sensitivity to IR radiation incident on the detector, and an electric field may be applied to collect the photoexcited carriers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates schematically an example of an embodiment of the present invention comprising several paired quantum well layers of III-V material, namely GaAs bounded by barrier layers of Al,Ga,As. FIG. 2 is an energy level diagram of the structure of FIG. 1.

FIG. 3 is a typical energy level diagram of a conventional IR detector using III-V material to form uniformly spaced quantum wells.

FIGS. 4a and 4b are energy level diagrams which are useful in understanding the principle of the present invention of coupling quantum wells having a single energy level, E,, as shown in FIG. 4a, by so reducing the spacing, W, between quantum wells as to split the single energy level into two levels, E, and E, by interaction. The difference, AE, between the two energy levels E, and E, is reduced for increased wavelength detection. Thus, by varying the well spacing W between paired quantum wells, AE can be made smaller for longer wavelength detection. Such a structure of coupled quantum wells is repeated to improve absorption, i.e., sensitivity to IR radiation incident on the detector, and an electric field may be applied to collect the photoexcited carriers.

FIG. 5 is a conduction band diagram of the present invention in FIG. 1 illustrating photoconductivity produced by absorption of intersubband radiation and tunneling of photoexcited electrons out of the wells.

DETAILED DESCRIPTION OF THE INVENTION

An example of the embodiment of the invention will now be described with reference to FIG. 1. A long wavelength IR detector 10 is shown comprised of paired layers 11 and 12 of semiconductor material 13, such as GaAs, bounded by barrier material, such as Al,Ga,As. The width of each paired layer of semiconductor material is W, and the spacing between the
paired layers is \( W_2 \), where \( W_2 \) is selected for the desired wavelength of IR radiation to be detected. FIG. 2 illustrates an energy level diagram for the coupled quantum wells of the layered structure in FIG. 1.

In the prior art, similar layered structures were provided to form quantum wells having two quantized energy levels, as shown in FIG. 3. \( E_1 \) with a symmetric wave function and \( E_2 \) with an antisymmetric wave function. To achieve the two energy levels, the depth, \( d \), and/or width, \( W \), of each quantum well must be relatively large, for example \( d = 200 \) meV, \( W = 65 \) Å. See B. F. Levine, K. K. Choi, C. G. Bethera, J. Walker and R. J. Malik, "New 10 \( \mu \)m infrared detector using intersubband absorption in resonant tunneling GaAlAs superlattices," Appl. Phys. Lett. 50, 1092 (1987). The basic quantum well structure is then repeated many times with large uniform spacing.

The principle of the present invention is to provide a reduced difference \( \Delta E \) of the quantum well energy levels \( E_1 \) versus \( E_2 \), in order to increase the wavelength of IR absorption, and to form the required symmetric and antisymmetric wave functions by using a physical principle which is fundamentally different from that used in the prior art. This is accomplished by using coupled quantum wells in pairs, as described with reference to FIGS. 1 and 2.

The manner of achieving coupling between quantum wells for a reduced \( \Delta E \) will now be described with reference to FIGS. 4a and 4b. In FIG. 4a, there is first shown an energy level diagram of two quantum wells formed with only a single quantized energy level \( E \). By reducing the spacing \( W_2 \) between the quantum wells until coupling between the wells is achieved (i.e., until the overlap of the wave functions is significant), the single energy level \( E \) is split into two levels \( E_1 \) and \( E_2 \) as shown in FIG. 4b. This coupling between the wave functions of the quantized energy levels in the paired wells is a function of the spacing or distance \( W_2 \) between the wells.

The corresponding isolated wells have the same single-quantum energy level \( E \) when the spacing \( W_2 \) between the wells is large, as illustrated in FIG. 4c. However, as the spacing \( W_2 \) is decreased, the wave function in the paired wells interact resulting in the formation of a symmetric and an antisymmetric wave function, and the energy levels split in a manner analogous to the formation of bonding and antibonding orbitals of molecular hydrogen which are formed from the atomic orbitals. Since the degree of wave function overlap, and hence the energy level splitting, can be varied by varying the spacing (barrier width) \( W_2 \) between the two coupled wells, a detector can be designed to operate at an arbitrary wavelength, as demonstrated by the following tables I and II.

### Table I

<table>
<thead>
<tr>
<th>( W_2 (Å) )</th>
<th>( E_1 (\text{meV}) )</th>
<th>( E_2 (\text{meV}) )</th>
<th>( \Delta E (\text{meV}) )</th>
<th>( \lambda (\mu\text{m}) )</th>
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</thead>
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<tr>
<td>14</td>
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<td>39.9</td>
<td>23.4</td>
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<td>17</td>
<td>17.2</td>
<td>39.2</td>
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<td>56.4</td>
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<td>17.4</td>
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<td>36</td>
<td>16.8</td>
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<tr>
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<td>20</td>
<td>35.5</td>
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<td>80</td>
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<td>36.8</td>
<td>20.4</td>
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<tr>
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<tr>
<td>42.5</td>
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<td>34</td>
<td>13</td>
<td>95.4</td>
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</table>

### Table II

<table>
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<tr>
<th>( W_2 (Å) )</th>
<th>( E_1 (\text{meV}) )</th>
<th>( E_2 (\text{meV}) )</th>
<th>( \Delta E (\text{meV}) )</th>
<th>( \lambda (\mu\text{m}) )</th>
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</thead>
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<tr>
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</tr>
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</table>

The barrier material used for the GaAs quantum wells in Table I was \( A_{0.06}Ga_{0.94}As \). The depth \( d \) of the wells was maintained constant (50 meV) as was the width of the wells (70 Å). The wavelength detection data shows that as the width \( W_2 \) of the barrier material is increased, the difference \( \Delta E \) in the split energy levels \( E_1 \) and \( E_2 \) decreases while the wavelength \( \lambda \) increases. For a shorter range of wavelengths shown in Table II, the concentration of Al in the barrier material was increased to increase the difference \( \Delta E \) in the split energy levels \( E_1 \) and \( E_2 \) to a range greater than the range of \( \Delta E \) in Table I. Then, by varying \( W_2 \) in nine steps, very similar to the eleven steps in Table I, and changing the well width \( W_1 \) and depth \( d \) to 42.5 Å and 100 meV, the wavelength response was increased progressively from 26.6 \( \mu \)m to 50 \( \mu \)m, a range below the wavelength range of 53 to 95.4 \( \mu \)m in Table I. From this data it is evident that for about the same range of well spacing, \( W_2 \), a different range of wavelength detection is achieved by varying the width and depth of the quantum wells. For longer wavelengths, the quantum well should be wider, and the depth should be less, but by increasing the spacing between paired quantum wells of the same parameters \( W_1 \) and \( d \) the wavelength detection increases, so that an IR detector may be designed for a desired wavelength of detected radiation. The reason the range of longer wavelength (Table I) is designed with a greater width \( W_1 \) and a smaller depth \( d \) is that for tunneling of photoexcited electrons, the upper level \( E_2 \) must be near...
the top of the quantum well, as may be appreciated from the discussion below with reference to FIG. 5. It is thus evident from the Tables I and II that for the present invention to work in the 10 to 100 µm wavelength range, energy level splittings of 12 to 120 meV are required, such as for example, an energy level splitting of 23.4 meV obtained using 70 Å thick GaAs wells, AlGaAs barriers and a width W2 for the barrier between the wells of 14 Å (Table I). Then by varying the spacing W2, the difference ΔE between the split levels E1 and E2 can, in principle, be made arbitrarily small to increase the wavelength of IR absorption. However, the spacing W2 can, in practice, be reduced from the large thickness of the prior art (~65 Å) to a minimum of about 10 Å, but increasing W2 can increase the wavelength of IR detected from about 10 µm to about 100 µm, provided the well width and depth is properly selected.

FIG. 5 illustrates a conduction band diagram for the structure of FIG. 1 with an electric field applied to provide avalanche gain from the intersubband absorption of IR radiation to produce photoexcited electrons, and tunneling of the electrons into an adjacent quantum well where impact ionization produces more electrons, thus producing avalanche gain. See B. F. Levine, K. K. Choi, C. G. Bethera, J. Walker and R. J. Malik, "Quantum well avalanche multiplication initiated by 10 µm photoexcited tunneling," Appl. Phys. Lett. 51, 934 (1987).

In summary the structure of the present invention is based on the energy level splitting induced by coupling between pairs of quantum wells, and the advantage over the prior art is providing for detection of long wavelength IR radiation for which satisfactory detectors did not previously exist. The restrictions on quantum well design parameters are not as severe in the present invention as compared to the prior-art intersubband absorption IR detectors, since an excited state (E2) within a single well is not required. Instead, the second energy level is effectively established by splitting the energy of coupled quantum wells which are provided in pairs. Additional degrees of freedom, and thus flexibility in design parameters, are available by using wells of different widths, asymmetric wells formed by different barrier heights, etc.

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art. Consequently, it is intended that the claims be interpreted to cover such modifications and variations.

I claim:
1. A device for infrared detection comprising an even number of quantum wells in a linear array, said quantum wells being paired, each odd numbered quantum well being paired with an adjacent even numbered quantum well, said quantum wells of each pair being coupled by selected spacing between said paired wells, each quantum well comprising a layer of well material bounded on each side by a layer of barrier material with a width and depth of each quantum well selected for a predetermined single energy level such that, when said single energy level is split by coupling between paired quantum wells, an upper and a lower energy level is produced, said selected spacing between paired quantum wells being selected for splitting said single energy level with a difference between said upper and lower energy levels appropriate for detection of infrared radiation of a desired wavelength greater than about 10 µm and up to about 100 µm.

2. A device as defined in claim 1 wherein said paired odd and even numbered quantum wells are selected to have the same width.

3. A device as defined in claim 1 wherein said paired odd and even numbered quantum wells are selected to have different widths for producing asymmetric wave functions and energy level splitting which is not symmetric about a single-well energy level.

4. A device as defined in claim 1 wherein said well material and said barrier material is the same, with doping of said well material using N-type impurities, and/or doping of said barrier material using P-type impurities, thereby creating conduction band discontinuities between layers of said quantum well material and said barrier material.

5. A device as defined in claim 1 wherein said well material is GaAs, and said barrier material is AlxGa1-xAs.

6. A device as defined in claim 5 wherein the depth of said paired quantum wells is 50 meV and the width of said paired quantum wells is 70 Å, the concentration x of Al in said barrier material is 0.06 for a difference in split energy levels of about 23.4 meV for a minimum spacing of about 14 Å, and the spacing between wells is selected from a range of about 14 Å to about 42.5 Å for radiation detection in a range of about 53 µm to about 95.4 µm.

7. A device as defined in claim 5 wherein the depth of said paired quantum wells is 100 meV, the width of said quantum wells is 42.5 Å, the concentration x of Al in said barrier material is made greater than 0.06 for a difference in split energy levels of about 46.6 meV for a minimum spacing of about 14 Å, and the spacing between wells is selected from a range of about 14 Å to about 36.8 Å for radiation detection in a range of about 26.6 µm to about 50 µm.

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