A method for converting a Type 2 quantum well semiconductor material to a Type 1 material. A second layer of undoped material is placed between first and third layers of selectively doped material, which are separated from the second layer by undoped layers having small widths. Doping profiles are chosen so that a first electrical potential increment across a first layer-second layer interface is equal to a first selected value and/or a second electrical potential increment across a second layer-third layer interface is equal to a second selected value. The semiconductor structure thus produced is useful as a laser material and as an incident light detector material in various wavelength regions, such as a mid-infrared region.
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CONVERSION OF TYPE OF QUANTUM WELL STRUCTURE

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a N.A.S.A. contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, as amended, Public Law 85-568 (72 Stat. 435; 42 U.S.C. §2457).

FIELD OF THE INVENTION

This invention relates to conversion of quantum well structures from one type to another type with higher optical transition strength.

BACKGROUND OF THE INVENTION

A semiconductor quantum well (QW) can be broadly classified as Type 1 (electron and hole wave functions overlap substantially) and Type 2 (electron and hole wave functions are substantially non-overlapping). Either type of QW relies upon decay of (free) electrons into (vacant) holes and thus upon overlap of the electron and hole wavefunctions near the recombination region so that a Type 2 QW structure will generally have a much smaller optical gain or associated electron-hole current than does a Type 1 QW structure. A semiconductor material such as InAs has an attractive band gap in the mid-infrared region, but materials such as AlSb/InAs in a conventional configuration appear to have only Type II band edge lineups. This precludes use of InAs, in a conventional QW configuration, from being used to produce, or to detect, light of mid-infrared wavelengths.

What is needed is an approach for converting a Type II QW material to a Type I QW material. Preferably, this approach should be flexible and should provide a spectrum of emission wavelengths in a selected wavelength band, such as a mid-infrared band. Preferably, this approach should work with a variety of choices of column III and column V semiconductor materials and with a continuum of geometric parameters associated with the QW wells. Preferably, this approach should allow use of the converted material for detection of the presence of light and/or for production of light in a specified wavelength band.

SUMMARY OF THE INVENTION

These needs are met by the invention, which provides an N-layer QW structure, with $N \geq 5$. In one embodiment, a five-layer semiconductor structure is provided, where the individual layers are doped, undoped, active, undoped and doped in that order, and the doping levels, locations and widths of the two doped layers are chosen so that overlap of electron and hole wavefunctions are sufficiently strong to have high optical transition strength.

One example, using InAs for the active region and AlSb for the doped regions is found to provide a Type 1 QW structure with adequate optical gain. The valence band offset between AlSb and InAs is taken to be 180 meV, which is the upper limit in the range of uncertainty. Proper doping in the heterostructure converts the InAs layer to a well for holes so that a Type II QW structure is thereby converted to a Type I QW structure. Both dipole moments and optical gain increase significantly with increasing doping.

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One example, using InAs for the active region and AlSb for the doped regions is found to provide a Type 1 QW structure with adequate optical gain. The valence band offset between AlSb and InAs is taken to be 180 meV, which is the upper limit in the range of uncertainty. Proper doping in the heterostructure converts the InAs layer to a well for holes so that a Type II QW structure is thereby converted to a Type I QW structure. Both dipole moments and optical gain increase significantly with increasing doping.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates construction of a five-layer, a six-layer and a seven-layer QW semiconductor structure, according to the invention.

FIGS. 2A and 2B graphically illustrate the conduction and valence band edge energy profiles for a seven layer structure of FIG. 1, for different doping levels.

FIGS. 3A and 3B graphically illustrate computed gain spectra for electron-hole density of $10^{12}$ cm$^{-2}$ for different doping densities.
The remaining portion of the QW layers, \( z(3) \leq z \leq z(6) \), is constructed by analogy to the first portion, \( z(1) \leq z \leq z(3) \). When \( V(z(3); \text{total}) = V_{ef} \) or \( V(z(3); \text{total}) > V_{ef} \), the total electrical potential \( V(z) \) behaves as illustrated in FIG. 2B for a symmetrical structure. For example, with \( z_{1,2} = 10 \text{ nm}, z_{3,4} = 10 \text{ nm}, N_p = 10^{18} \text{ cm}^{-3} \) and \( \epsilon_p = 10, V(z) = 181 \text{ meV}, \) which is already close to the target value of 180 meV. The structure \( 10 \) in FIG. 1 may be symmetric or non-symmetric. Here, the layers \( 11-1 \) and \( 11-3 \) have doping densities of \( 10^{18} \text{ cm}^{-2} \) or of \( 3 \times 10^{18} \text{ cm}^{-2} \).

By reducing or eliminating the hole barrier at the interface \( z = z(3) \) (and similarly at \( z = z(4) \)), the hole wavefunctions are permitted to substantially overlap with the electron wavefunctions, and the structure \( 10 \) in FIG. 1 becomes a Type I QW structure, where the optical field is preferably polarized in the \( z \)-direction and propagates primarily within the third layer material (e.g., InAs). Where the third layer material is InAs, the band gap lies in the mid-infrared range so that wavelengths produced or sensed in this range may be provided.

FIG. 1 also illustrates a six-layer structure, defined by \( z(0) \leq z \leq z(6) \) or by \( z(1) \leq z \leq z(7) \), where the added layer, \( 11-0 \) or \( 11-6 \), has zero doping. The results at the interfaces, \( z = z(3) \) and \( z = z(4) \), are the same: a Type II QW structure is converted into a Type I QW structure.

The QW structure shown in FIG. 1 can serve as a laser material that produces mid-infrared wavelength laser light, and can serve as a photodetector material for production of electron hole pairs in response to receipt of mid-infrared (and lower) wavelengths.

What is claimed is:

I. A method for converting a Type II quantum well (QW) structure including III–V semiconductor material to a Type I QW structure, the method comprising:

- providing first and third spaced apart layers of respective first and third III–V semiconductor donor materials,
- having selected first layer and third layer widths, respectively, each in a width range of about 1–30 nm;
- providing a second layer of a second III–V semiconductor material, contiguous to and lying between the first layer and the third layer, having a selected second layer width in a width range of about 1–30 nm and having a selected negative potential relative to potentials of the first layer and the third layer;
- doping a first layer first component, having a width that is less than the first layer width and is in a width range of about 1–20 nm, with a first layer doping level in a doping range of about \( 1 \times 10^{18} \text{ cm}^{-2} \), and providing a first layer second component that is substantially undoped and lies between and is contiguous to the first layer first component and to the second layer; and
- doping a third layer first component, having a width that is less than the third layer width and is in a width range of about 1–20 nm, with a third layer doping level in a doping range of about \( 1 \times 10^{18} \text{ cm}^{-2} \), and providing a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer.

The QW structure shown in FIG. 1 can serve as a laser material that produces mid-infrared wavelength laser light, and can serve as a photodetector material for production of electron hole pairs in response to receipt of mid-infrared (and lower) wavelengths.
2. The method of claim 1, further comprising applying a structure comprising said first, second and third layers to at least one of the following: (1) as, a laser material, to provide at least one laser emission wavelength in a mid-infrared wavelength region; and (2) as a photodetector material, to provide an electron-hole current in response to receipt of light having a wavelength no greater than a mid-infrared wavelength.

3. Apparatus for providing or detecting presence of light in a mid-infrared wavelength region, the apparatus comprising:

first and third spaced apart layers of respective first and third III-V semiconductor donor materials, having selected first layer and third layer widths, respectively, each in a width range of about 1-30 nm;

a second layer of a second III-V semiconductor material, located contiguous to and lying between the first layer and the third layer, having a selected second layer width in a width range of about 1-30 nm and having a selected negative potential relative to potentials of the first layer and the third layer,

where the first layer: has a first layer first component, having a width that is less than the first layer width and is in a width range of about 1-20 nm, with a first layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a first layer second component that is substantially undoped and lies between and is contiguous to the first layer first component and to the second layer; and

where the third layer: has a third layer first component, having a width that is less than the third layer width and is in a width range of about 1-20 nm, with a third layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer,

and

where the first layer component and third layer first component doping levels and the first layer and third layer widths are chosen so that at least one of the following conditions is satisfied: (1) a change in electrical potential across an interface between the first and second layers is equal to a first selected potential value and (2) a change in electrical potential across an interface between the second and third layers is equal to a second selected potential value.

4. The apparatus of claim 3, incorporated in a structure as a laser material, to provide at least one laser emission wavelength in a mid-infrared wavelength region.

5. The apparatus of claim 3, incorporated in a structure as a photodetector material, to provide an electron-hole current in response to receipt of light having a wavelength no greater than a mid-infrared wavelength.

6. A method for converting a Type II quantum well (QW) structure including III-V semiconductor material to a Type I QW structure, the method comprising:

providing first and third spaced apart layers of respective first and third III-V semiconductor donor materials, having selected first layer and third layer widths, respectively, each in a width range of about 1-30 nm;

providing a second layer of a second III-V semiconductor material, contiguous to and lying between the first layer and the third layer, having a selected second layer width in a width range of about 1-30 nm and having a selected negative potential relative to potentials of the first layer and the third layer.

and the third layer, having a selected second layer width in a width range of about 1-30 nm and having a selected negative potential relative to potentials of the first layer and the third layer wherein the first layer second component width and the third layer second component width are unequal;

doping a first layer first component, having a width that is less than the first layer width and is in a width range of about 1-20 nm, with a first layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and providing a first layer second component that is substantially undoped and lies between and is contiguous to the first layer first component and to the second layer;

and providing a fourth layer of semiconductor material, having a selected fourth layer width, substantially undoped and contiguous to the first layer first component, so that the first layer first component lies between the fourth layer and the first layer second component;

doping a third layer first component, having a width that is less than the third layer width and is in a width range of about 1-20 nm, with a third layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and providing a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer,

and

where the first layer first component and third layer first component doping levels and the first layer and third layer widths are chosen so that at least one of the following conditions is satisfied: (1) a change in electrical potential across an interface between the first and second layers is equal to a first selected potential value and (2) a change in electrical potential across an interface between the second and third layers is equal to a second selected potential value.

7. The method of claim 6, further comprising providing a fifth layer of semiconductor material, having a selected fifth layer width and being substantially undoped, contiguous to said third layer first component so that said third layer first component lies between the fifth layer and said third layer second component.

8. Apparatus for providing or detecting presence of light in a mid-infrared wavelength region, the apparatus comprising:

first and third spaced apart layers of respective first and third III-V semiconductor donor materials, having selected first layer and third layer widths, respectively, each in a width range of about 1-30 nm;

a second layer of a second III-V semiconductor material, located contiguous to and lying between the first layer and the third layer, having a selected second layer width in a width range of about 1-30 nm and having a selected negative potential relative to potentials of the first layer and the third layer,

where the first layer: has a first layer first component, having a width that is less than the first layer width and is in a width range of about 1-20 nm, with a first layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a first layer second component that is substantially undoped and lies between and is contiguous to the first layer first component and to the second layer; and

where the third layer: has a third layer first component, having a width that is less than the third layer width and is in a width range of about 1-20 nm, with a third layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer,

and

where the first layer component and third layer first component doping levels and the first layer and third layer widths are chosen so that at least one of the following conditions is satisfied: (1) a change in electrical potential across an interface between the first and second layers is equal to a first selected potential value and (2) a change in electrical potential across an interface between the second and third layers is equal to a second selected potential value.

40 8. Apparatus for providing or detecting presence of light in a mid-infrared wavelength region, the apparatus comprising:

first and third spaced apart layers of respective first and third III-V semiconductor donor materials, having selected first layer and third layer widths, respectively, each in a width range of about 1-30 nm;

a second layer of a second III-V semiconductor material, located contiguous to and lying between the first layer and the third layer, having a selected second layer width in a width range of about 1-30 nm and having a selected negative potential relative to potentials of the first layer and the third layer,

where the first layer: has a first layer first component, having a width that is less than the first layer width and is in a width range of about 1-20 nm, with a first layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a first layer second component that is substantially undoped and lies between and is contiguous to the first layer first component and to the second layer; and

where the third layer: has a third layer first component, having a width that is less than the third layer width and is in a width range of about 1-20 nm, with a third layer doping level in a doping range of about (1-100)x10^{11} cm^{-2}; and has a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer,

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where the first layer component and third layer first component doping levels and the first layer and third layer widths are chosen so that at least one of the following conditions is satisfied: (1) a change in electrical potential across an interface between the first and second layers is equal to a first selected potential value and (2) a change in electrical potential across an interface between the second and third layers is equal to a second selected potential value.

7. The method of claim 6, further comprising providing a fifth layer of semiconductor material, having a selected fifth layer width and being substantially undoped, contiguous to said third layer first component so that said third layer first component lies between the fifth layer and said third layer second component.
first layer first component lies between the fourth layer and the first layer second component;
where the third layer has a third layer first component, having a width that is less than the third layer width and is in a width range of about 1-20 nm, with a third layer doping level in a doping range of about (1-100)×10^{11} cm^{-2}; and has a third layer second component that is substantially undoped and lies between and is contiguous to the third layer first component and to the second layer, and
where the first layer first component and third layer first component doping levels and the first layer and third layer widths are chosen so that at least one of the following conditions is satisfied: (1) a change in electrical potential across an interface between the first and second layers is equal to a first selected potential value and (2) a change in electrical potential across an interface between the second and third layers is equal to a second selected potential value.

9. The apparatus of claim 7, further comprising a fifth layer of semiconductor material, having a selected fifth layer width and being substantially undoped and located contiguous to said third layer first component so that said third layer first component lies between the fifth layer and said third layer second component.

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