

DUAL BAND INFRARED DETECTOR USING STEP MULTIQUANTUM WELLS WITH SUPERLATTICE BARRIERS

FIELD OF INVENTION

This invention relates generally to multiple quantum well infrared detectors, and more particularly, to detection of more than one wavelength using a multiple quantum well structure consisting of step quantum wells and superlattice barriers.

5 BACKGROUND OF INVENTION

There are a number of infrared detector materials and technologies which have been used for fabrication of infrared detectors. For infrared detection using interband transitions in the wavelength range of 3~20 μ m, semiconductors with narrow bandgap materials (e.g., InSb, HgCdTe) are commonly used. For these materials, there exist
10 difficulties associated with instability of the composition and processing which result in problems of reproducibility and uniformity of large area arrays. However, quantum well infrared detectors based on intersubband transitions are constructed using chemically stable wide-bandgap materials. This construction overcomes the disadvantages mentioned above and achieves response wavelength tunability with the use of bandgap engineering
15 principles.

The quantum well infrared photodetectors (QWIPS) based on intersubband transitions have been extensively investigated in recent years. Because of mature III-V material and processing technology, quantum well structure with novel properties can be fabricated based on intersubband transitions. For example, multicolor infrared detectors

that can give high discrimination ability of objects and imaging under various atmospheric conditions have been explored using asymmetric quantum well structures.

According to known selection rules, symmetric square quantum well structures can have only one response wavelength due to the transition from the ground state to the first excited state. To get response in several wavelength ranges, one approach is to build several stacks of square quantum wells with different peak response wavelengths. The response due to different wavelengths can be achieved either by contacting each stack separately or by controlling the bias across the stacks to sequentially activate different stacks. Another approach is to use asymmetric quantum wells or coupled quantum wells where transitions from the ground state to several excited states can occur. This approach provides the advantage of requiring only one set of quantum wells, which simplifies fabrication. The photoexcited carries are extracted by controlling the bias across the device.

Step quantum wells have been used for the fabrication of infrared modulators and multi-color detectors. The multiple step quantum wells were separated by thick barriers, and thus, required a high electric field in the device to extract the photoexcited electrons through the thick barriers. However, such a high bias can produce the disadvantage of a large leakage current, especially at high operating temperatures of about 77 °K and may therefore result in poor detectivity. Another disadvantage of this structure is that the photocurrent due to the ground to first excited state transition cannot be collected unless the first excited state lies close to the top of the barrier. This greatly limits the tunability of the detection wavelength.

SUMMARY OF THE INVENTION

The concepts of the present application overcome substantial disadvantages of known detectors using quantum wells by providing a dual band infrared detector using step quantum wells with superlattice barriers instead of thick barriers. The detector uses bound-to-miniband (BM) and bound-to-continuum (BC) intersubband transitions in step quantum wells. The bound-to-miniband photocurrent is extracted by using superlattice barriers at a relatively low applied electric field. Thus spectrum tunability of the photocurrent is achieved by adjusting the energy level in the step well relative to a miniband by an external bias. Discrimination of the photocurrents due to BM and BC

transitions using the linear Stark effect (Stark shift) of the energy levels in the quantum well. The superlattice barriers have a miniband aligned with an excited state in the quantum well to allow for high temperature operation by using photocarrier transport via the miniband.

5 It is accordingly apparent that the detector of the present invention is substantially improved over the known prior art.

 Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications
10 within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

 The present invention will become more fully understood from the detailed
15 description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

 Figure 1a is a schematic view illustrating a dual band infrared detector in accordance with an embodiment of the present invention;

 Figure 1b is a schematic view further illustrating the layers of the step quantum
20 wells and superlattice barriers shown in Figure 1a;

 Figure 2 is the band diagram of the quantum well structure used for two wavelength detection;

 Figure 3 is the band diagram of the quantum well structure under an external bias showing the transport of carriers via miniband and continuum states;

25 Figure 4 is an energy band diagram of the quantum well showing the location of the energy levels;

 Figure 5 illustrates the measured absorption as a function of photon energy of the dual wavelength step quantum well detector with superlattice barriers at room temperature;

Figure 6 illustrates the measured photoresponse at $T = 77^\circ\text{K}$ for two different detector bias voltages; and

Figure 7 illustrates the incident infrared radiation on the detector.

DETAILED DESCRIPTION OF THE INVENTION

5 The exemplary embodiments of the invention claimed in the appended claims may be more fully appreciated by reference to the following description of preferred embodiments. Within the drawing figures, it should be understood that like elements are identified by like reference numbers.

10 An exemplary dual wavelength detector based on a quantum well structure and superlattice barrier is described with reference to figures 1a and 1b of the instant application. The structure of the detector 10 has 40 periods of step quantum wells 12 and superlattice barriers 14. Each step quantum well consists of a 30 Å thick $n\text{-In}_x\text{Ga}_{1-x}\text{As}$ layer 32 doped with Si to about $1 \times 10^{18} / \text{cm}^3$ and a 73 Å thick undoped GaAs layer 34. The superlattice barriers 14 that separates the quantum wells 12 consist of undoped 5-
15 periods of 51 Å thick GaAs layers 36 and 40 Å thick $\text{Al}_y\text{Ga}_{1-y}\text{As}$ layers 38. The entire structure is sandwiched between top 1 μm and bottom 1 μm $n\text{-GaAs}$ layers 16 doped with Si to about $1 \times 10^{18} / \text{cm}^3$ for ohmic contacts.

20 The entire structure was grown by molecular beam epitaxy (MBE) at a reduced substrate temperature ($\sim 530^\circ\text{C}$) on a semi-insulating GaAs substrate 18 to avoid the relaxation of the strain in the InGaAs layer. The thickness of the $n\text{-InGaAs}$ layer 32 in the step quantum well is kept below the critical thickness corresponding to the 30% In composition. The thicknesses of layers 32, 34, 36, 38 and the compositions of layers 32, 38 can be varied to tune the detection wavelengths of the detector. An example method for varying the thicknesses of the layers to provide the desired detector frequencies is
25 given by R. People and J.C. Bean, "Calculation of Critical Layer Thickness Versus Lattice Mismatch for $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ Strained-layer Heterostructures", in Appl. Phys. Lett. 47 (3), 1 August 1985.

30 Figure 2 shows the band diagram of the quantum well structure used for two wavelength detectors. The two transitions shown are bound-to-miniband (BM), and bound-to-continuum (BC). The first miniband of the superlattice is aligned with the first excited state of the step quantum well so that the photocurrent transport occurs through

the miniband. This avoids the tunneling of carriers through a relatively thick barrier and hence can improve the collection efficiency of the photocurrent. The position of the miniband can be conveniently adjusted by the proper selection of the superlattice parameters. This allows tuning of detector wavelength by controlling the parameters of the step well.

The two-color detection is achieved by using bound-to-miniband (BM) and bound-to-continuum (BC) transitions in the step quantum well. The superlattice barriers provide efficient transport of photoexcited electrons under an external bias via the minibands as depicted in Figure 3 while suppressing the thermionic emission, resulting in a smaller dark current.

Figure 4 shows the locations of the energy states of the step quantum well. There are two bound energy states below the barrier (1, 2) and a continuum energy band above the barrier (3). The lack of symmetry of the potential in the step quantum well allows both $1 \rightarrow 2$ and $1 \rightarrow 3$ intersubband transitions. The oscillator strength of the transition from ground state to the first excited state $1 \rightarrow 2$ is calculated to be about 0.69 and the integrated oscillator strength of the transitions from ground state to the continuum band $1 \rightarrow 3$ is about 0.31. The oscillator strength for the $1 \rightarrow 2$ transition is selected to be higher since the mobility of the photoexcited electrons through the first miniband is low compared to the continuum to have nearly equal photoresponses for the two transitions.

Regarding Figure 6, the shift of the peak positions for the different biases is due to the linear Stark effect associated with the step quantum well. At low bias, the first excited state $1 \rightarrow 2$ is designed to align with the miniband of the superlattice barrier and the photocurrent via the miniband increases as the bias increases due to higher carrier velocity. However, at high bias the excited state $1 \rightarrow 2$ shifts away from the miniband which affects the transport of carriers due to the lack of coherency and results in a smaller responsivity. Such a behavior is clearly seen from the bias dependent photocurrent spectra in Figure 6.

The absorption of the sample is measured by a Fourier transform infrared (FTIR) spectrometer using a waveguide structure at room temperature. A waveguide made of GaAs with similar dimensions is used as the reference in the measurement. The absorption due to bound-to-miniband and bound-to-continuum transitions are clearly observed at two well separated wavelengths as shown in Figure 5. The two intersubband

transitions are possible since the asymmetric quantum well relaxes the parity selection rule ($\Delta n = 1$) for the intersubband transitions.

For the photoresponse measurement, mesa diodes of 200 μm in diameter are fabricated using standard photolithography techniques and wet chemical etching. The spectral dependence of the photocurrent is measured using a infrared source and a grating monochromator with a lock-in detection. As shown in Figure 7, infrared is illuminated on the mesa using a 45° facet polished on the wafer in order to enhance the coupling of infrared with the bound electrons in the quantum well and overcome the polarization selection rule of the intersubband transition. Two peaks in the photoresponse at 6 μm and 12 μm wavelengths are observed (see Figure 5) due to the two transitions in the step quantum well. The positions of the two peaks are in good agreement with that observed in the absorption measurement. The use of superlattice barriers allowed us to operate the detector at 77°K without appreciable degradation of the signal, and thus, demonstrates the possibility of the use of superlattice barriers for the fabrication of multi-color detectors.

It should be apparent from the aforementioned description and attached drawings that the concept of the present application may be readily applied to a variety of preferred embodiments including those disclosed herein. Accordingly, the scope of the invention described in the instant application should be limited solely by the appended claims.

CLAIMS:

- 1 1. A dual band infrared detector, comprising:
2 an asymmetric step quantum well arrangement having a plurality of wells
3 including a first well defining a bound state and a second well defining a first excited
4 state;
5 a plurality of superlattice barriers, each barrier located between successive
6 wells to form alternating layers of wells and barriers;
7 a miniband formed among the superlattice barriers and aligned with the
8 first excited state to provide photocurrent transport along the miniband; and
9 a second energy state and a continuum energy band formed above the
10 barriers to provide photocurrent transport along the continuum energy band, wherein
11 multiple color detection is achieved by measuring photocurrent at a bound-to-miniband
12 transition and at a bound-to-continuum transition.
- 1 2. The dual band infrared detector of claim 1, wherein each barrier includes
2 periods of GaAs and AlGaAs layers, and each well includes a doped InGaAs layer and
3 an undoped GaAs layer.
- 1 3. The dual band infrared detector of claim 1, further comprising a first
2 contact layer formed over a top alternating layer, and a second contact layer formed
3 under a bottom alternating layer.



1 4. The dual band infrared detector of claim 3, further comprising an external
2 bias applied to the first and second contact layers.

1 5. The dual band infrared detector of claim 4, wherein the photocurrent is
2 tunable by applying the bias to adjust an energy level in the well relative to the miniband.

1 6. The dual band infrared detector of claim 1, wherein the photocurrent at the
2 bound-to-miniband transition and at the bound-to-continuum transition is discriminated
3 by Stark shift of an energy level in the wells.

1 7. The dual band infrared detector of claim 1, wherein the detector is
2 operable ∇ about 77°K.
 up to

3 8. A method of detecting more than one wavelength using a dual band
4 infrared detector, comprising:

5 a. forming an asymmetric step quantum well arrangement having a
6 plurality of wells including a first well defining a bound state and a second well defining
7 a first excited state;

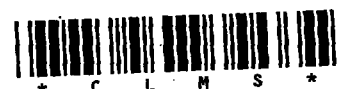
8 b. forming a plurality of superlattice barriers, each barrier located
9 between successive wells to form alternating layers of wells and barriers;

10 c. forming a miniband among the superlattice barriers;

11 d. aligning the miniband with the first excited state to provide
12 photocurrent transport along the miniband; and

13 e. forming a second energy state and a continuum energy band above
14 the barriers to provide photocurrent transport along the continuum energy band, wherein
15 multiple color detection is achieved by measuring photocurrent at a bound-to-miniband
16 transition and at a bound-to-continuum transition.

1 9. The method of claim 8, wherein each barrier includes periods of GaAs and
2 AlGaAs layers, and each well includes an InGaAs layer and a GaAs layer, and further
3 comprising doping the InGaAs well layer with Si.



1 10. The method of claim 8, further comprising forming a first contact layer
2 over a top alternating layer, and forming a second contact layer under a bottom
3 alternating layer.

1 11. The method of claim 10, further comprising applying an external bias to
2 the first and second contact layers.

1 12. The method of claim 11, further comprising tuning the photocurrent by
2 applying the bias to adjust an energy level in the well relative to the miniband.

1 13. The method of claim 8, further comprising discriminating the photocurrent
2 at the bound-to-miniband transition and at the bound-to-continuum transition by Stark
3 shift of an energy level in the wells.

1 14. The method of claim 8, further comprising operating the detector at about
2 77°K.

