DEVELOPMENT OF NEW III-V SEMICONDUCTOR QUANTUM WELL INFRARED PHOTODETECTORS FOR MID- AND LONG-WAVELENGTH INFRARED DETECTION

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1994
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the chairman of my committee, Professor Sheng S. Li, for his guidance, encouragement, and support during the course of this research. I would also like to thank Professors A. Neugroschel, G. Bosman, R. Srivastava, and T. Anderson for serving on my supervisory committee.

I am grateful to Dr. P. C. Yang for many beneficial discussions and much help in programmed control of the optical measurement system. I am also grateful to many friends and colleagues, including Drs. L. S. Yu, Y. C. Wang and F. Gao, along with D. Wang, J. C. Chiang, J. Chu, and C. S. Lee, for their helpful discussions and valuable assistance in the device fabrication and measurements.

Special thanks are extended to Dr. Pin Ho of Martin Marietta for the MBE growth of the III-V QWIP structures and to Dr. K. C. Chou for the growth of the GaAs/InGaP QWIP using MOCVD.

I am greatly indebted to my parents, wife, and daughter for their love, support and patience during the course of this study.

Finally, the financial support of ARPA is gratefully acknowledged.
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DEVELOPMENT OF NEW III-V SEMICONDUCTOR QUANTUM WELL INFRARED PHOTODETECTORS FOR MID- AND LONG-WAVELENGTH INFRARED DETECTION

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August 1994

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In this dissertation, three types of III-V semiconductor quantum well infrared photodetectors (QWIPs) have been developed for 3-5 µm mid-wavelength infrared (MWIR) and 8-14 µm long-wavelength infrared (LWIR) detection. They are (1) GaAs/AlGaAs, GaAs/InGaP bound-to-continuum (BTC) QWIPs and InGaAs/InAlAs bound-to-miniband (BTM) QWIP, (2) normal-incidence type-II indirect bandgap AlAs/AlGaAs QWIP, and (3) normal-incidence p-type strained-layer InGaAs/InAlAs and InGaAs/GaAs QWIPs. These QWIP structures were grown by the molecular beam epitaxy (MBE) technique, with the exception of the GaAs/InGaP QWIP, which was grown by the metal-organic chemical vapor deposition (MOCVD) technique. Detectivity ranging from 10⁹ to 10¹² cm·√Hz/W was obtained for these QWIPs at T = 77 K.

The BTC and BTM QWIPs exhibited both photoconductive (PC) and photovoltaic (PV) dual-mode (DM) detection characteristics. The peak wavelengths for the GaAs/AlGaAs QWIP were found to be at 7.7 µm and 12 µm. The peak wavelengths
for the GaAs/InGaP QWIP were found to be at 6.0 μm and 8.2 μm. The voltage-tunable InGaAs/InAlAs QWIP showed a peak wavelength of 10 μm with dual-mode operation.

A normal-incidence type-II indirect bandgap AlAs/AlGaAs QWIP grown on (110) GaAs substrate was developed, which shows a multicolor detection feature with peak response wavelengths occurred at 2.2, 2.7, 3.5, 4.8, 6.5, and 12.5 μm. Extremely large photoconductivity gains of 630 and 3,200 at peak wavelengths of 3.5 and 2.2 μm were obtained at \( V_b = 3 \) and 6 V, respectively, while a broad spectral photoresponse with peak wavelength at 12.5 μm was observed.

A normal-incidence p-type tensile strained-layer InGaAs/InAlAs QWIP grown on InP substrate with an ultralow dark current density (about six orders of magnitude smaller than the standard GaAs/AlGaAs QWIP) was developed in this work. This QWIP has achieved background limited performance (BLIP) for \( T \leq 100 \) K, which is the highest BLIP temperature ever reported for a QWIP. The detectivity for this QWIP was found to be \( D^*_{BLIP} = 5.9 \times 10^{10} \text{ cm-VHz/W} \) at peak wavelength of 8.1 μm, \( V_b = 2 \) V, and \( T = 77 \) K. Finally, a normal-incidence p-type compressive strained-layer InGaAs/GaAs QWIP grown on GaAs substrate was also demonstrated for the first time in this work, which showed a two-color detection feature with peak wavelengths at 5.5 μm and 8.9 μm.
CHAPTER 1
INTRODUCTION

Infrared photodetectors are transducers that can convert invisible IR radiation into a measurable electrical signal, and their arrays can be used as imaging sensors in military, industrial, medical treatment, and scientific research applications. Infrared radiation was discovered in 1800 [1], and it covers wavelengths ranging from 0.75 \( \mu m \) to 1000 \( \mu m \) as shown in Fig. 1.1. In the entire infrared radiation spectrum, wavelengths ranging from 1 \( \mu m \) to 20 \( \mu m \) were found to be very important in the image applications. In atmospheric window applications, there are three main detection bands: (1) 1-3 \( \mu m \) short-wavelength infrared (SWIR), (2) 3-5 \( \mu m \) mid-wavelength infrared (MWIR), and (3) 8-14 \( \mu m \) long-wavelength infrared (LWIR) (see Fig. 1.2). The 1-3 \( \mu m \) band has been found to be very attractive in fiber optical communications. The 8-14 \( \mu m \) band is preferred for high performance thermal imaging sensors because of its great sensitivity to ambient temperature objects and its better transmission through the atmosphere, while the 3-5 \( \mu m \) band is more appropriate for hotter object detection or if sensitivity is less important than contrast.

Infrared detectors can be classified into two broad types, namely thermal detectors and photon (quantum) detectors. Thermal detectors such as bolometers and pyroelectric detectors are made from temperature-sensitive materials. When IR radiation is absorbed, the temperature of a thermal detector increases, which in turn produces a measurable electrical signal. Due to its response to thermal power, the thermal detector usually suffers from a low detectivity and a fairly slow response time, but it can be operated at ambient temperature. Photodetectors are fabricated from semiconductors whose electrical conductivity can be modulated by photon-induced transitions that excite carriers from bound states into mobile states. The detectors
respond only to incident photons with energy equal to or greater than the difference between transition states. Photodetectors can be operated at two detection modes: photoconductive (PC) and photovoltaic (PC) modes. In some practical applications, the PV mode operation may be more preferred than the PC mode detection due to its low noise level, low power dissipation, and large array size. The primary photodetectors used for thermal imaging in past decades are summarized in Table 1.1. In LWIR detectors, the most important detectors are fabricated from ternary compounds, HgCdTe (MCT). However, due to the volatility, high dislocation density, small wafer size, different temperature expansion between the MCT and silicon readout circuits, and processing difficulties in the MCT, progress has been very slow for LWIR image sensor applications.

Recent advances in epitaxial layer growth techniques such as Molecular Beam Epitaxy (MBE) and Metalorganic Chemical Vapor Deposition (MOCVD) enable the growth of semiconductor heterolayers with atomically sharp interfaces. With the advent of these epitaxial growth techniques, significant progress has been made in multiquantum well and superlattice optoelectronic devices. The atmospheric window infrared detection of the 3-5 μm MWIR and the 8-14 μm LWIR bands can be realized by using the quantum well and superlattice heterostructures.

Studies of heterojunction superlattices and their transport properties were first reported by Esaki and Tsu [2, 3]. Due to coupling effects between adjacent quantum wells, the resonant tunneling behavior between the different states of adjacent wells along the superlattice growth axis was observed in AlAs/GaAs system by Esaki and Chang [4]. The quantization of the energy states in the quantum wells was experimentally verified through the optical measurement by Dingle et al. [5]. In the quantum well and superlattice structures, the carriers are confined in the quantized states of the quantum wells, and they can transport either in the parallel within the wells or in the perpendicular along the superlattice growth axis. The parallel transport with
wavevectors $k_x$ and $k_y$ can give rise to two-dimensional electron gap (2-DEG) properties such as high electron mobility transistors (HEMTs), whereas in the perpendicular transport carriers can move along the superlattice growth axis with the wavevector $k_z$, resulting in a much larger mobility difference between confined bound states and upper excited conduction states due to blocking potential barriers on the two sides of the well.

In quantum well infrared photodetectors (QWIPs), the conducting carriers transport along superlattice axis so as to suppress the dark current associated with the populated ground state and to enhance the photocurrent collection through the upper excites states. The excited states can be either the continuum states or the miniband states. In the continuum state conduction, the excited carriers can become the hot carriers with higher mobility at applied bias voltage, while in the miniband state conduction, the excited carriers can transport resonantly through the global miniband states. However, there are two different conduction processes in the miniband states: (1) hopping conduction and (2) coherent miniband conduction. When the barrier layers of a superlattice are thick (i.e., isolated quantum wells) or a strong electric field is applied to the superlattice, the energy states become localized (i.e., Kane states) [6], and the carrier transport is dominated by the hopping conduction through the quantum wells. On the other hand, if the barrier layers of a superlattice are thin enough or applied bias is relatively low, wavefunction overlapping appears near adjacent wells and the miniband (Bloch states) conduction [7] is expected to be the dominant conduction process. In the miniband conduction scheme, the superlattice effective mass filtering effect [8] was observed, and a giant photocurrent gain was achieved in the interband transition. The following unique features were observed in the miniband conduction: (1) reduction of heterointerface recombination in optoelectronic devices, (2) elimination of deep-levels-related photoconductive phenomena, (3) realization of coherent tunneling through miniband conduction, and (4) large oscillator strength.
In general, based on the energy bandgap alignments, the heterointerface multi-quantum well/superlattice structures may be divided into four types: type I, type II staggered, type II misaligned, and type III (see Fig. 1.3). Type I alignment occurs when the bandgap of one semiconductor lies completely within the gap of the other, in which both electrons and holes are confined within the same narrower gap layers, for example, GaAs/AlGaAs, InGaAs/InAlAs, GaAs/InGaP, and GaSb/AlSb. Type II staggered alignment results when two materials overlap but one does not completely enclose the other, and electrons and holes are confined in the different semiconductor layers such as ZnSe/ZnTe and CdSe/ZnTe materials. Type II misalignment arises if the band gaps of the two materials do not overlap at all in energy such as InAs/GaSb material. Type III alignment appears in heterojunctions containing a semimetallic compound such as HgTe/CdTe material. In these four types of heterointerfaces, it has been widely believed that high quality epitaxial layers could only be grown on the lattice matched substrates. However, the high quality epilayers could also be grown in slightly lattice-mismatched material systems if the individual epilayer thickness is within the critical thickness. In these lattice mismatched quantum well and superlattice structures, either tensile strain or compressive strain may be intentionally introduced [9]. Due to the strain effects, dislocation lines from the lattice mismatch can be locally confined within the layers, hence the mismatch is fully accommodated by the elastic strain.

In 1985, West and Eglash [10] first observed an extremely large dipole infrared intersubband absorption strength from a GaAs quantum well structure; they called this intersubband transition a quantum well envelope state transition (QWEST). This new dipole intersubband transition is ascribed to the “momentum vector reorientation” between the envelope states, and the Bloch states remain nearly constant. In contrast, the dipole transition from conduction to valence bands occurs between the Bloch states, and the envelope states remain constant. Based on the new intersub-
band transitions, Levine et al. [11] demonstrated the first GaAs/AlGaAs quantum well infrared photodetector (QWIP) based on bound-to-bound (BTB) intersubband transition for 8-14 μm LWIR detection. Since then, the rapid progress in QWIP performance has been made based on bound-to-continuum [12, 13], bound-to-miniband [14] intersubband transition schemes. Figure 1.4 shows the energy bandgaps and lattice constants of some III-V and II-IV compound materials used for the QWIP fabrication. The detectivity of the GaAs/AlGaAs LWIR QWIP for operating at photoconductive mode has been improved dramatically to the point where large 128 × 128 staring focal plane arrays have now been demonstrated [15, 16]. In addition, the imaging sensor arrays using GaAs/AlGaAs LWIR QWIPs for operating on the photovoltaic (PV) mode have also been reported [17]. Table 1.2 lists the performance status of the GaAs/AlGaAs QWIP at T = 77 K. The QWIPs for the 3-5 μm MWIR detection using the intersubband transitions have also been investigated using InGaAs/InAlAs and AlGaAs/GaAs material systems [18, 19]. However, QWIP arrays used for the atmospheric spectral window of both MWIR and LWIR bands have not been demonstrated yet. The image sensors at both the MWIR and the LWIR bands offer practical applications in tracking-and-searching and forward-looking infrared (FLIR) systems. The development of III-V semiconductor QWIPs for MWIR and LWIR detection is the main motivation of this dissertation.
Table 1.1. Primary photon detectors for mid- and long-wavelength infrared detection.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mode</th>
<th>Operating T (K)</th>
<th>λ (μm)</th>
<th>Array Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb</td>
<td>PC</td>
<td>195</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC, PV</td>
<td>77</td>
<td>5.7</td>
<td>640×840</td>
</tr>
<tr>
<td>PbSe</td>
<td>PC</td>
<td>195</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>77</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>PbTe</td>
<td>PC</td>
<td>77</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>PtSi</td>
<td>Schottky</td>
<td>77</td>
<td>5.1</td>
<td>1024×1024</td>
</tr>
<tr>
<td>Pb$<em>{17}$Sn$</em>{83}$Te</td>
<td>PV</td>
<td>77</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Hg$<em>{0.799}$Cd$</em>{0.201}$Te</td>
<td>PC, PV</td>
<td>77</td>
<td>13</td>
<td>128×128</td>
</tr>
</tbody>
</table>
Table 1.2. Performance status of the GaAs/AlGaAs QWIPs at $T = 77$ K.

<table>
<thead>
<tr>
<th>Year</th>
<th>Single or Array</th>
<th>mode</th>
<th>$\lambda_p$ (\textmu m)</th>
<th>$D_\alpha^*$ cm$^{-1}$Hz/W</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Single</td>
<td>PC</td>
<td>8.0</td>
<td>$4 \times 10^{10}$</td>
<td>[12]</td>
</tr>
<tr>
<td>1990</td>
<td>Single</td>
<td>PC</td>
<td>10</td>
<td>$2 \times 10^9$</td>
<td>[13]</td>
</tr>
<tr>
<td>1991</td>
<td>Single</td>
<td>PC</td>
<td>8.9</td>
<td>$1.6 \times 10^{10}$</td>
<td>[14]</td>
</tr>
<tr>
<td>1991</td>
<td>128x128</td>
<td>PC</td>
<td>7.7</td>
<td>$5.8 \times 10^9$</td>
<td>[15,16]</td>
</tr>
<tr>
<td>1992</td>
<td>4x4</td>
<td>PV</td>
<td>7.5</td>
<td>—</td>
<td>[17]</td>
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</table>
Figure 1.1. Chart of electromagnetic spectrum.
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Figure 1.4. Energy bandgap versus lattice constant for some III-V and II-VI compound semiconductor materials.
CHAPTER 2
QUANTUM WELL AND SUPERLATTICE STRUCTURES

2.1. Introduction

The introduction of quantum well (QW) and superlattice structure makes it possible to design and fabricate various novel quantum devices. Long wavelength infrared (LWIR) photodetectors using the superlattice and quantum well structures have been extensively investigated based on bound-to-bound [11, 20], bound-to-quasicontinuum [21], bound-to-miniband [14], bound-to-continuum [12, 22], and miniband-to-miniband [23, 24] intersubband transition mechanisms. In order to understand the optical and electrical properties of quantum well and superlattice structures, it is necessary to study them from both macroscopic and microscopic theories.

2.2. Methods for Calculating Electronic States

A crystal is made up of a large number of interacting particles, positive nuclei surrounded by negative electrons. The nuclei form a rigid lattice that is completely frozen at low temperatures. As the temperature is raised, nuclei vibrate about their mean positions, as described by phonons. Consequently, the theoretical treatment of the energy levels and wavefunctions in solids cannot be attempted without a number of simplifying approximations. We can write the total Hamiltonian of the system in the form

\[ H_t = T_e + T_N + V_{ee} + V_{eN} + V_{NN}, \]  

(2.1)

where \( T_e \) and \( T_N \) are the kinetic energy of electrons and nuclei, respectively, and \( V_{ee} \), \( V_{eN} \), and \( V_{NN} \) are the electron-electron, electron-nuclei, and nuclei-nuclei interactions,
respectively. Since the strongest force between particles in a solid is due to coulomb interaction, the kinetic (T) and potential (V) energy terms can be expressed as

\begin{align}
T &= -\sum \frac{\hbar^2}{2m^*} \nabla^2 \\
V &= \sum \frac{Z e^2}{4\pi \varepsilon_0 |r_i - r_j|},
\end{align}

where \( Z = 1 \) is for the electron, otherwise for the nuclei charges.

The system Schrödinger equation can be written as

\[ H_t \Psi(R, r) = E \Psi(R, r). \]

The system wavefunction \( \Psi(R, r) \) can be expressed as the product of the nuclei wavefunction \( \chi(R) \) and the electron wavefunction \( \psi(R, r) \),

\[ \Psi(R, r) = \chi(R) \psi(R, r) \]

where \( R \) represents the space and spin coordinates of the nuclei and \( r \) denotes the coordinates for the electrons. This eigenvalue problem can be further simplified for electronic states by using some basic approximations.

Due to the extremely different masses between the electrons and the nuclei, the eigenvalue problem can be split into two separate, though interdependent, eigenvalue problems for electrons and nuclei by using the \textit{adiabatic approximation} [25], which assumes that electrons will adiabatically follow the lattice (or nuclei) vibration. The eigenvalues for electrons and nuclei can be solved from

\begin{align}
[T_e + V_{ee} + V_{en}]\psi_n(R, r) &= E_n(R)\psi_n(R, r); \\
[T_N + V_{nn} + E_n(R)]\chi(R) &= E_n\chi(R),
\end{align}

where subscript \( n \) denotes a quantum number of the coordinates for the electrons. Even though we have the electron eigenvalue expression, this still represents a very complicated many-body problem. However, most of the systems such as the super-lattice can be described by using the \textit{one-electron approximation}, which assumes that
the motion of a single electron experiences some average force due to vibrating lattice and all other particles. These one-electron wavefunctions satisfy the self-consistent Hartree-Fock equations [26]. The solution of the Hartree-Fock equation is still a very difficult mathematical problem. For this reason, the band approximation is often employed, i.e., one solves the Schrödinger equation with an assumed crystal potential $V(r)$ [27]. The time-independent one electron Schrödinger equation and the potential are given by

$$\left[-\frac{\hbar^2 \nabla^2}{2m^*} + V(r)\right] \psi_n(k, r) = E_n(k) \psi_n(k, r),$$  \hspace{1cm} (2.8)

$$V(r) = V_L(r) + V_E(r) + V_S(r),$$  \hspace{1cm} (2.9)

where $V_L$ represents the perfect lattice periodic potential, $V_E$ is the superlattice periodic potential, and $V_S$ is the random scattering potential. Figure 2.1 schematically shows the three components of $V(r)$. The wavefunction of the electron is $\psi_n(k, r)$ and the eigenvalue of the electron in the k-space for n-th band is $E_n(k)$. For example, near the bottom of the conduction band, the eigenvalues of electrons in a superlattice can be described by

$$E_n(k) = E_n(k_z) + \frac{\hbar^2}{2m^*_z}(k_x^2 + k_y^2),$$  \hspace{1cm} (2.10)

where $E_n(k_z)$ is the energy dispersion relation along the superlattice axis (longitudinal) and other terms are the energy dispersion relations within the superlattice plane (transverse).

There are two different but equivalent procedures for obtaining the energy states and wavefunctions with the band approximation, which assumes that potential is invariant for all symmetry operations. These two procedures are (1) expand the crystal states on a complete set of Bloch type function and then determine the expansion coefficients by requiring the states to satisfy the appropriate Schrödinger equation, such as the tight binding method, the orthogonal plane wave (OPW) method, or the pseudopotential method, and (2) expand the states on a complete set of functions that are solutions of the Schrödinger equation within a unit cell and then determine
the expansion coefficients by the appropriate boundary conditions, such as the cellular method, the augmented plane wave (APW) method, or the Green's function method. As a practical matter one has to choose, from physical considerations, the method whose set of basis function sufficiently represents the exact eigenfunction within the band approximation. Besides the two basic analytical procedures above, semi-empirical approaches and interpolation schemes (i.e., k.p theory) are also very powerful tools in determining effective masses and densities of states (DOS) near high symmetry points in k space such as k = 0 of Brillouin zone center. Based on the k.p method, calculations of the band structure of a superlattice have been carried out by using the Kronig-Penney model and the modifications of the boundary condition [28]. The nonparabolicity effects in the band structures have been taken into account by using the Kane model [6].

By considering only the periodic potential $V_L(r)$ in $V(r)$ (ignoring $V_E$ and $V_S$), the solution of the Schrödinger equation is the Bloch type wavefunction,

$$\psi_{n,k}(r) = U_{n,k}(r)exp(ik \cdot r), \quad (2.11)$$

where $U_{n,k}(r)$ is a periodic function with the same periodicity as $V_L$ and $n$ denotes the band index. By considering slow varying potential $V_E$ and random scattering potential $V_S$ and using calculated dispersion relation $E_n(k)$, the eigenvalues and eigenfunctions can be solved by using the effective mass envelope function approach. The effective mass envelope equation for n-th band can be written as

$$[E_n(-i\nabla) + V_E + V_S]\phi_n(r) = E\phi_n(r), \quad (2.12)$$

where $\phi_n(r)$ is the envelope function and $E$ is the eigenvalues that satisfy the effective mass equation. If the multiband model is incorporated in the effective mass equation, summation over band index $n$ is required.

If the superlattice growth is along z-direction (x- and y-directions within super-
lattice plane), then the Bloch function becomes

\[ \psi_{n,k}(r) = U_{n,k}(z) exp(ik_x x + ik_y y) \]  

(2.13)

and the envelope function \( \phi_n(r) \) becomes a function of coordinate \( z \), that is, \( \phi_n(z) \).

### 2.3. Superlattice and Miniband

In conventional quantum wells, carriers are confined within potential barriers that are formed by energy band gap offset between two materials. In order to reduce the tunneling dark current from the ground states in the quantum wells, the use of thicker barrier layers between the wells is very important for high performance of the QWIPs. However, these QWIP structures suffer from the large dark current due to the defect existence in the thicker barrier layers. In order to overcome this problem, very short period superlattice barrier layers are introduced to replace the thicker barrier layers [14]. The superlattice barriers can confine the defects within the thin layer and significantly reduce the dark current. The replacement of the superlattice barrier layer offers several new features over the conventional quantum wells. They are (1) improvement of the roughness at the heterojunction interfaces by superlattice smoothing, (2) reduction of interface recombination, (3) elimination of deep-levels-related phenomena [29], and (4) realization of a coherent conduction with large quantum photocurrent gain [8].

The superlattice barrier quantum wells also involve the confinement of carriers and the determinations of energy eigenvalues and wavefunctions in the heterostructure. When the carrier de Broglie wavelength becomes comparable to the barrier thickness of the superlattice, the wavefunctions of the individual wells tend to overlap due to tunneling, hence the global minibands are formed. The miniband decoupling occurs when the bias voltage across one period of the superlattice becomes larger than the miniband bandwidth. From the carrier transport point of view, the
superlattice can have an adjustable effective barrier height by properly selecting superlattice structure parameters. Due to the adjustability of the superlattice, carrier conduction through the superlattice can be tuned and modulated by the miniband intrinsic transport properties, such as coherent tunneling conduction and ballistic resonant conduction.

2.3.1. Dispersion Relations

In an A-B type-I (two different materials) superlattice with growth direction along the z-axis, one period of the alternating layers is called the basis of the superlattice, denoting L (= La + Lb, La for wells and Lb for barriers). Since the superlattice period L is much longer than the lattice constant, the Brillouin zone is divided into a series of minizones, leading to a narrow subband (or miniband). As a result, the actual wavefunction of a superlattice is the product of the Bloch wavefunction, which is a periodic function of the atomic potential, and the envelope wavefunction, which is a function of the superlattice potential,

$$\psi(k, r) = \sum_n \phi_n(z) U_{n,k}(z) \exp(ik_x x + ik_y y), \quad \text{(2.14)}$$

where summation is over the band index n and $k_{x,y}$ are the transverse wavevectors in x- and y-direction.

In the effective mass approximation and using the one-band Kronig-Penney model, the envelope wavefunction $\phi_n(z)$ can be written as [30]

$$\phi_n(z) = \begin{cases} 
C_1 \cos[k_a(z - L_a/2)] + C_2 \sin[k_a(z - L_a/2)] & \text{in the well} \\
C_3 \cos[k_b(z + L_b/2)] + C_4 \sin[k_b(z + L_b/2)] & \text{in the barrier},
\end{cases} \quad \text{(2.15)}$$

where

$$k_a = \frac{[2m^*_a(E - E_a)]^{1/2}}{\hbar}, \quad \text{(2.16)}$$

$$k_b = \frac{[2m^*_b(E - E_b)]^{1/2}}{\hbar}, \quad \text{(2.17)}$$

$C_{1-4}$ are constants that depend on boundary conditions and subband index parity, $E_{a,b}$ are band minima or maxima for the well and barrier layers.
Bastard [28] has shown that, in the parabolic band approximation, the dispersion relation for the unbound states is

\[ \cos [k_z (L_a + L_b)] = \cos (k_a L_a) \cos (k_b L_b) - \frac{1}{2} (1/\xi + \xi) \sin (k_a L_a) \sin (k_b L_b) \]  

(2.18)

with \( \xi = m^*_b k_a / m^*_a k_b \) and \( k_z \) defines the superlattice wavevector.

The dispersion relation for the bound states is still valid if one substitutes \( k_b \) by \( i \kappa_b \) and \( \xi \) by \( -i \xi' \) with \( \xi' = m^*_b k_a / m^*_a \kappa_b \),

\[ \cos [k_z (L_a + L_b)] = \cos (k_a L_a) \cosh (\kappa_b L_b) - \frac{1}{2} (1/\xi' - \xi') \sin (k_a L_a) \sinh (\kappa_b L_b) . \]  

(2.19)

The minibands for the bound and unbound states can be obtained from Eqs. (2.18) and (2.19). The higher minibands could extend above the potential barriers. However, the electron in-plane wavefunction of superlattice experiences only a regular lattice periodicity, and the dispersion relations in transverse direction (i.e., \( k_x \) and \( k_y \)) are much like those for unperturbed cases (i.e., Bloch type wavefunction).

It is noted that transverse wavevectors \( k_x, k_y \) are conserved across the interfaces since the interface potential in the envelope function approximation depends only on the \( z \) coordinate. However, the spatially dependent effective masses are not entirely decoupled and are \( 3 \times 3 \) tensors, which introduces nonparabolicity to the subbands. The bandwidth of a miniband is an exponential function of the superlattice barrier thickness \( L_b \),

\[ \Gamma \sim \exp(-CL_b), \]  

(2.20)

where \( C \) is a constant. The miniband bandwidths and miniband energy levels versus barrier thickness are illustrated in Fig. 2.2. It is noted that the bandwidth becomes wider and wider as the barrier thickness decreases.

Another feature in superlattice is the effective mass modulation. The effective mass \( m_x \) of a miniband can be deduced from the dispersion relation \( E_n(k_x) = E' \)
A smaller effective mass $m_z^*$ with higher electron mobility for both wells and barriers can be obtained along superlattice axis. The wider the miniband bandwidth is, the smaller the tunneling time constant becomes. When the tunneling time is much smaller than the carrier relaxation time and scattering time, a coherent and ballistic carrier conduction through the miniband can be built up, which is desirable for QWIP applications.

The above results hold for a perfect superlattice with a flat band diagram, ignoring the effects of growth layer fluctuations and roughness, electron-electron interaction, electron-phonon interaction, and depolarization. In reality, all these corrections to energy states and wavefunctions should be incorporated in the calculations of the miniband properties. In order precisely to analyze superlattice miniband dispersion relations, the two-band or three-band model should be used in which interband and intervalley interactions are included (see Appendix A).

2.3.2. Transmission Probability $|T \cdot T|$  

The transmission probability through a superlattice can be calculated numerically by using the transfer matrix method [31]. The carrier conduction in each layer of the superlattice potential regions consists of superposition of two components propagating in the forward and backward directions, respectively. The total wavefunctions can be written as

$$\psi_i = \psi_i^+ e^{-i\Delta_i} e^{i\Delta_i} + \psi_i^- e^{i\Delta_i} e^{-i\Delta_i}$$  (2.23)

where

$$\Delta_1 = \Delta_2 = 0,$$
$$\Delta_i = k_i(d_2 + d_3 + \cdots + d_i)$$
where $\psi_i^+$ and $\psi_i^-$ represent the magnitudes of the particle wave functions propagating along the $+z$ and $-z$ directions, respectively, $N$ is the number of the period of a superlattice, and $d_i$, $m_i^*$, $E_i$ are the thickness, effective mass, and potential energy of $i$-th layer in the superlattice, respectively. Since $\psi$ and $d\psi/dz$ are continuous at the boundaries, we obtain

$$\psi_i^+ = (e^{-i\delta_i} \psi_{i+1}^+ + r_i e^{-i\delta_i} \psi_{i+1}^-)/t_i$$

$$\psi_i^- = (r_i e^{i\delta_i} \psi_{i+1}^+ + e^{i\delta_i} \psi_{i+1}^-)/t_i.$$ 

Here the recurrence relation may be written in matrix form

$$\begin{pmatrix} \psi_i^+ \\ \psi_i^- \end{pmatrix} = \frac{1}{t_i} \begin{pmatrix} e^{-i\delta_i} & r_i e^{-i\delta_i} \\ r_i e^{i\delta_i} & e^{i\delta_i} \end{pmatrix} \begin{pmatrix} \psi_{i+1}^+ \\ \psi_{i+1}^- \end{pmatrix},$$

where (at normal incidence)

$$r_i = \frac{k_i - k_{i+1}}{k_i + k_{i+1}},$$

$$t_i = \frac{2k_i}{k_i + k_{i+1}},$$

$$\delta_i = k_i d_i.$$ 

Thus, we have

$$\begin{pmatrix} \psi_1^+ \\ \psi_1^- \end{pmatrix} = S_1 \begin{pmatrix} \psi_2^+ \\ \psi_2^- \end{pmatrix} = S_1 S_2 \begin{pmatrix} \psi_3^+ \\ \psi_3^- \end{pmatrix} = \cdots = S_1 S_2 \cdots S_N \begin{pmatrix} \psi_{N+1}^+ \\ \psi_{N+1}^- \end{pmatrix}.$$ 

Since there is no backward propagating component in the last medium, i.e., $\psi_{N+1}^- = 0$, one can find $\psi_i^+ (i = 2, 3, \ldots, N+1)$ in term of $E_1^+$, where $i$ represents the layer region to be investigated. If we calculate the quantity $\frac{\psi_i^+}{\psi_i^-}$ as a function of $E$, then we can obtain the resonant peaks with Lorentzian distribution. The transmission probability is given by

$$|T \cdot T| = \left| \frac{\psi_1^+}{\psi_1^-} \right|^2.$$
2.4. Carrier Transports

The carrier transport in the QWIPs plays a key role in the performance of QWIPs. In general, the carrier conduction processes in the quantum well/superlattice structures are quite complicated. Basically, they can be divided into three different conduction processes: the continuum state conduction, the miniband conduction, and the hopping conduction.

2.4.1. Continuum State Conduction

When the excited states of a QWIP lie above the quantum well barrier, the states become continuum states, which have 3-dimensional (3-D) conduction properties. Charge carriers (i.e., either dark or photoexcited carriers) that transport through the continuum states generally have high mobility under applied bias conditions. If the electric field is high enough, then hot carrier conduction through the 3-D continuum states is expected. This type of conduction has advantages of high efficiency, high photoconductive gain, and long mean free path. In fact, if the excited state is placed just above the barrier, resonant infrared absorption and maximum oscillator strength can be obtained [32]. This type of the conduction is usually the dominant transport process in a bulk barrier QWIP.

2.4.2. Miniband Conduction

The miniband conduction is a coherent resonant tunneling process in which photoexcited carriers are phase-coherent to the incident IR radiation. This coherent conduction can lead to much higher carrier transmission probability through the quantum well and superlattice. Resonant transmission mode builds up in the miniband to the extent that the scattering reflected wave is cancelled out and the conduction transmitted wave is enhanced. The miniband conduction depends strongly on the miniband bandwidth, heterointerface quality, and layer thickness fluctuation. For example, it has been demonstrated that the morphological quality of the heterointerface can be greatly improved by using interruption growth technique for a few tens of seconds [33].
The interruption growth allows one to reduce the density of monolayer terraces in the plane of the heterointerface. As a result, the interface improvement can enhance the coherence of the interfacing electron wave overlapping and resonant coupling. In the miniband conduction, the effective mass of the photoexcited electrons can be modulated by superlattice structure parameters, given by \( m^*_e = (2\hbar^2)/\Gamma L^2 \). An effective mass \( m^*_e \) for the miniband smaller than that of both the wells and barrier may be obtained. As a result, photoexcited electron transport in the miniband will have a higher electron mobility, which leads to a large oscillator absorption strength, high quantum efficiency, and high response speed. Furthermore, increasing the miniband bandwidth will reduce the tunneling time constant (i.e., \( \tau_0 = \hbar/\Gamma = 6.6 \times 10^{-16}/\Gamma \) in eV). The value of \( \tau_0 \) in a QWIP is estimated to be about 20 fs (for \( \Gamma = 30 \sim 70 \) meV), while a scattering time constant \( \tau_S \) typically is about 0.1 ps. Thus, for \( \tau_0 \ll \tau_S \), the coherent resonant tunneling can be built up in the miniband conduction process. The photocurrent strongly depends on the tunneling time constant \( \tau_0 \), while the intersubband relaxation time constant \( \tau_R \) is about 0.4 ps. From the theoretical calculation, \( \tau_0 \) is found to be about 20 to 100 fs, hence \( \tau_0 \ll \tau_R \). Thus, the photoexcited electrons can tunnel resonantly out of the quantum well/superlattice barrier via global miniband states.

In the miniband conduction, charge carrier transport through miniband states inside the quantum well has an average wavevector \( k_z = eF\tau_R/\hbar \), where \( F \) is the applied electric field. The drift velocity \( v_d \) along the superlattice axis can be expressed as

\[
v_d = \frac{\Gamma L}{2\hbar} \sin \left( \frac{eF\tau_R L}{\hbar} \right). \tag{2.34}
\]

At low electric field, the carrier mobility along the superlattice axis is given by

\[
\mu_z = \frac{e\Gamma L^2}{2\hbar^2} \tau_R. \tag{2.35}
\]

It is noted that the mobility is proportional to the miniband bandwidth \( \Gamma \) and the relaxation time \( \tau_R \) if the superlattice basis \( L \) is kept constant. Since the miniband
bandwidth is an exponential function of the superlattice barrier thickness, the carrier mobility is also sensitive to the thickness of the superlattice barrier layer. A similar conclusion can also be drawn from the Boltzmann equation using the relaxation time approximation.

2.4.3. Hopping Conduction

When the miniband conduction fails to form coherent conduction at higher electric field, the incoherent conduction becomes the dominant mechanism, which is referred to as the sequential resonant tunneling with a random wave phase. In the incoherent conduction, the states in the quantum wells (i.e., Kane state) become localized within the individual well, and the carriers will transport via phonon-assisted tunneling (hopping) with a frequency of $eFL/h$. A better approach for analysis of the incoherent hopping conduction is to utilize the carrier scattering mechanism. Carrier scattering tends to destroy the coherency of the wavefunctions, hence the fully resonant threshold value will never be built-up. The mobility of the hopping conduction is usually much lower than that of the miniband conduction. As the barrier layer thickness or the thickness fluctuation increases, the maximum velocity $v_{\text{max}} (= \Gamma L/2\hbar)$ and the carrier mobility decrease. This is due to the fact that the relaxation time is nearly independent of superlattice period $L$. The mobility for the hopping conduction can be expressed as [34]

$$
\mu_s \approx \frac{eL^2 A}{k_B T} \exp \left[ -\frac{8m^*}{h^2} \frac{(\Delta E - E_1)}{1/2} \right].
$$

(2.36)

It is worth noting that the product of $v_{\text{max}} \cdot \tau_R$ is always greater than the mean free path $L_p$ in the miniband conduction. However, it will reduce to even smaller than the superlattice period $L$ in the hopping conduction limit. When the QWIPs are operating at cryogenic temperature, phonon-assisted tunneling is suppressed, and other scattering sources such as ionized impurities, intersubband levels, and interface roughness can also play an important role in the tunneling conduction.
2.5. Corrections on Subband Energy States

2.5.1. Electron-Electron Interaction

In the calculations of electronic states in quantum well/superlattice structures, electron-electron interactions should be taken into consideration when the quantum well is doped to $10^{18}$ cm$^{-3}$ or higher. The interaction includes two components, direct Coulomb force and quantum exchange interaction, which shift energy states in opposite directions. The Coulomb interaction shifts the subband up while the exchange interaction shifts down. In type-I quantum wells, the doping in the quantum well can give rise to charge neutrality within the well, and the exchange energy is more significant than that of Coulomb interaction.

In the one-electron approximation, the solution of the Hartree-Fock equation gives the self-consistent eigenfunctions $\psi_n$ and eigenvalues $E_n$. The Hartree-Fock equation can be written as

\[
-\frac{\hbar^2}{2m^*} \nabla^2 \psi_n(r) + V(r)\psi_n(r) + \sum_m \int \frac{e^2}{4\pi\epsilon|r-r'|}\psi_m(r')^2\psi_n(r) dr' = E_n \psi_n(r).
\]

The third and fourth terms on the left-hand side of the above equation are the direct Coulomb and exchange interaction terms, respectively.

The exchange interaction energy term associated with electrons in the bound ground state is approximately given by [35]

\[
E_{exch}(k = 0) \approx -\frac{e^2k_F}{4\pi\epsilon} \left[ 1 - 0.32\frac{k_F}{k_1} \right],
\]

\[
E_{exch}(k_F) \approx -\frac{e^2k_F}{4\pi\epsilon} \left[ \frac{2}{\pi} - 0.32\frac{k_F}{k_1} \right],
\]

where $k_1 = \pi/L_a$, $k_F = (2\pi\sigma)^{1/2}$, and $\sigma = L_aN_D$ is the two-dimensional electron density in the quantum well. For the unpopulated excited states, the exchange-induced energy shift is very small, hence the dominant contribution to the energy
shift is due to the electron-electron interaction in the highly populated ground bound state. Figure 2.3 shows a typical exchange-induced energy shift for \( N_D = 10^{18} \text{ cm}^{-3} \) and \( L_a = 100 \text{ Å} \).

The energy shift in the ground bound state due to the direct coulomb interaction is given by [36]

\[
E_{direct} = \frac{3e^2}{8\epsilon k_F^2 L_a}.
\]  

(2.40)

This term has a small contribution to the energy shift compared to the exchange-induced energy shift (seen in Fig. 2.3).

2.5.2. Depolarization Effects

When IR radiation is impinging on a QWIP, resonant screening of the infrared field by electrons in the quantum well generates a depolarization field effect, which can cause the subband energy shift (also called the plasmon shift). The depolarization effect arises when the external field is screened by the mean Hartree field, which is caused by the other electrons polarized by the external field. The energy shift between subband \( E_0 \) and \( E_1 \) due to depolarization field effect is given by [37]

\[
E_{dep} = \sqrt{\frac{2e^2(E_0 - E_1)S_{01}}{\epsilon L_a}},
\]  

(2.41)

where \( S_{01} \) is the Coulomb matrix element given by

\[
S_{01} = \int_0^\infty dz \left[ \int_0^z \phi_0(z')\phi_1(z')dz' \right]^2.
\]  

(2.42)

It is noted that the depolarization effect increases as dopant density increases (see Fig. 2.3).

2.5.3. Other Effects

Besides the corrections discussed above on energy states, the temperature shift [38], band nonparabolicity [39], and band bending effect [40] due to dopant migration can also alter the energy states in the wells, which make the deviation from the effective mass approximation. However, compared with the correction from the exchange
energy and depolarization effect, these effects give only a small correction on subband energy states.
Figure 2.1. Three components of the potential energy $V(r)$ of electrons: $V = V_L + V_E + V_S$, (a) perfect lattice periodic potential $V_L$, (b) superlattice periodic potential $V_E$, and (c) random scattering potential $V_S$. 
Figure 2.2. Illustration of miniband energy levels and their bandwidths as a function of the superlattice barrier width.
Figure 2.3. Calculated energy shifts due to the direct Coulomb interaction, the electron-electron interaction, and the depolarization effect for $N_D = 10^{18}$ cm$^{-3}$ and $L_a = 100$ Å.
CHAPTER 3
PRINCIPLES OF QWIP OPERATION AND FIGURES OF MERIT

3.1. Introduction

Recently, rapid progress has been made in the development of high performance quantum well infrared photodetectors (QWIPs) [11-23]. The 128×128 imaging sensor arrays using GaAs/AlGaAs QWIPs for 8 to 14 μm LWIR detection have been demonstrated by using hybrid technology [15, 16]. The detectivity of the LWIR QWIPs has been improved dramatically in recent years and is now high enough to allow fabrication of large two-dimensional (2-D) staring focal plane arrays (FPAs) with performance comparable to the state-of-the-art MCT IR FPAs.

QWIPs fabricated from III-V material systems such as GaAs/AlGaAs and InGaAs/InAlAs offer a number of potential advantages over MCT material. These include (1) III-V material growth by using MBE or MOCVD is more matured than MCT, (2) monolithic integration of III-V QWIPs with GaAs readout circuits on the same chip is possible, (3) GaAs substrates are larger, cheaper, and higher quality than MCT, (4) III-V materials are more thermal stable than MCT, (5) higher yield, lower cost, and higher reliability is expected in III-V QWIPs than in MCT devices, and (6) III-V QWIPs have inherent advantages in both transient and total dose radiation hardness compared to MCT detectors.

3.2. Intersubband Transition

The intersubband transition in a QWIP takes place between the subband levels of either the conduction band or the valence band. It has some unique features, which include (1) large absorption coefficient [10], (2) narrow absorption bandwidth [41],
(3) large optical nonlinearity [42], (4) fast intersubband relaxation [43], (5) reduced Auger effect [44], (6) wavelength tunability [45], and (7) large photocurrent gain. The intersubband transition process can be analyzed by using the dipole transition model [46]. The transition rate $W$ from the initial state $\psi_i$ to the final state $\psi_f$ can be described by

$$W_{i\rightarrow f} = \frac{2\pi}{\hbar} \sum_f |\langle \psi_f | V_p | \psi_i \rangle|^2 \delta(E_f - E_i - \hbar \omega),$$

where $\omega$ is the incident photon frequency and $V_p$ is the interaction potential between the incident IR radiation and the electrons, which is given by [47]

$$V_p = \frac{eA_o}{m_e c} \hat{\epsilon} \cdot \mathbf{P},$$

where $A_o$ is the vector potential, $c$ is the speed of light in vacuum, $m_e$ is the free-electron mass, $\mathbf{P}$ is the momentum operator of electron, and $\hat{\epsilon}$ is the unit polarization vector of the incident photons.

Since the electron wavefunction $\psi_n(k, r)$ in the quantum well is the product of Bloch function $\psi_{n,k}(r) (= U_{n,k}(z) \exp(ik_xx + ik_yy))$ and the envelope function $\phi_n(z)$, the transition matrix element can be approximated by

$$M_{if} = \langle \psi_{n,k} | V_p | \psi_{n,k} \rangle_i$$

$$\sim \langle \psi_{n,k} | V_p | \phi_{n} \rangle_i \langle \phi_{n} | V_p | \phi_{n} \rangle$$

$$= \langle \psi_{n,k} | V_p | \phi_{n} \rangle_i \langle \phi_{n} | V_p | \phi_{n} \rangle_i.$$ (3.3)

In the interband transition scheme, the dipole transition occurs between the Bloch states while the envelope states (or momentum vectors) holds constant, hence the second term on the right-hand side of Eq. (3.3) tends to vanish. However, in the intersubband transition scheme such as QWIPs, the dipole transition is between the envelope states while the Bloch states remain nearly constant, thus the first term on the right-hand side of Eq. (3.3) becomes zero. From the calculation of the transition matrix element $M_{if} = \langle \psi_f | V_p | \psi_i \rangle$, the transition selection rules and the incident polarization requirement for the intersubband transition can be determined.
Finally, the absorption coefficient $\alpha$ can be calculated by using the expression [47]

$$\alpha_{i\rightarrow f} = \frac{2\pi \hbar c W_{i\rightarrow f}}{n_r A_2^6 \omega}, \quad (3.4)$$

where $n_r$ is the refractive index of the medium. This absorption coefficient curve can be fitted by the Lorentzian function. The integrated absorption strength $I_A$ for the polarized incidence radiation at the Brewster angle is given by

$$I_A = \sigma N S \frac{e^2 \hbar}{4 \epsilon_0 m^* c n_r^2 \sqrt{n_r^2 + 1}} \frac{f_{os}}{\Phi}, \quad (3.5)$$

where $N$ is the number of quantum wells, $S$ is the quantum well structure factor, and $f_{os}$ is the dipole oscillator strength given by

$$f_{os} = \frac{4 \pi m^* c}{\hbar \lambda} \left( \int_{-L_d/2}^{L_d/2} \psi_f \psi_i dz \right)^2. \quad (3.6)$$

When the incident radiation is perpendicular to the quantum well surface, transition matrix element $M_{if}$ is zero if the shape of constant energy surface of the material is spherical. A nonzero transition rate can be obtained by using either a 45° polished facet illumination or a grating coupler [48] for the spherical constant energy surface materials. For a transmission grating coupler, the grating equation is given by

$$n_r \sin \theta_m - \sin \theta_i = m \lambda_p / \Lambda, \quad (3.7)$$

where $\lambda_p$ is the resonant incident wavelength, $\Lambda$ is the grating period, $\theta_{i,m}$ denote the incident and the m-th order diffracted angle with respect to the superlattice axis, respectively. In a grating coupled QWIP, the integrated absorption strength $I_A$ in Eq. (3.5) should be multiplied by a factor of $\sin^2 \theta_m / \cos \theta_m$. 

3.3. PC and PV Detection Modes

A photodetector may be operated in either the photoconductive (PC) mode or the photovoltaic (PV) mode. In the BTC QWIPs, most of the them are operated in the photoconductive (PC) mode and a few are operated in the photovoltaic (PV) mode. However, in the BTM QWIPs, they may be operated in the PC and PV dual-mode detection because of the bandwidth modulation effect in the miniband conduction QWIPs.

A photoconductor exhibits a change in resistance $\Delta R_d$ when IR radiation is impinging on it. This change of the resistance is due to the generation of the mobile carriers in the photoconductor. The photogenerated carriers $\Delta n$ can be written as

$$\Delta n = \frac{\eta \Delta \Phi \tau_L}{V'}$$

(3.8)

where $\eta$ is the quantum efficiency, $\Delta \Phi$ is the incident photon flux, $\tau_L$ is the excess carrier lifetime, $V'$ is the volume of the detector. The photogenerated carriers will transport in the detector under applied bias, thus resulting photovoltage signal. The change in output photovoltage $\Delta V_o$ due to the resistance change is given by

$$\Delta V_o = -\frac{V_o R_L \Delta R_d}{(R_L + R_d)^2},$$

(3.9)

where $R_L$ is the load resistance and its value is chosen to be about equal to $R_d$ in order to give optimized output signal.

When a QWIP operates in the photovoltaic detection mode, the photogenerated carriers can be transported in the detector without using externally applied bias. An internal built-in potential, $V_{bi}$, can be created in the bound-to-miniband intersubband transition, which is due to the growth asymmetry and effective mass filtering effect through the global miniband. In the PV mode detection, the QWIP has an extremely low dark current, and the detector noise is dominated by Johnson noise which is much lower than that of the PC mode detection. The PV mode detector performance can be evaluated by $R_d A_d$ product, where $A_d$ is the active area of the detector.
3.4. Figures of Merit

In designing a quantum well infrared photodetector, it is important to understand the key parameters that determine the performance of a QWIP. They include: the dark current $I_d$, noise equivalent power (NEP), responsivity (R), and detectivity $D^*$. The QWIP performance can be evaluated by these parameters, which are often called the figures of merit.

3.4.1. Dark Current $I_d$

In a quantum well infrared photodetector, the dark current is due to both the thermionic emission and tunneling conduction. In a conventional QWIP, thermionic emission conduction is dominant, whereas in a BTM QWIP thermionic-assisted tunneling conduction through the miniband is dominant. In order to achieve a background limited performance (BLIP) in a QWIP, the dark current must be kept below the background photocurrent (also called window current).

In the low-field regime, the thermionic emission current is related to the density of mobile carriers $n_t$ and the average drift velocity $v_d$. It can be expressed as [49]

$$I_{th} = A_d e v_d n_t,$$

(3.10)

where $A_d$ is the detector active area, and

$$v_d = \frac{\mu F}{[1 + (\mu F/v_s)^2]^{1/2}},$$

(3.11)

$$n_t = \frac{m^* k_B T}{\pi \hbar^2 L} \exp[-(E_{cut} - E_F)/(k_B T)].$$

(3.12)

Here $v_s$ is the saturation drift velocity, $E_{cut}$ is the cutoff energy related to the cutoff wavelength $\lambda_c$, and $m^*/\pi \hbar^2$ is the 2-dimensional density of states. The Fermi level $E_F$ can be obtained from

$$N_D = \frac{m^* k_B T}{\pi \hbar^2 L_a} \sum_n \ln \left[ 1 + \exp \left( \frac{E_F - E_n}{k_B T} \right) \right]$$

(3.13)

$$\approx \frac{m^*}{\pi \hbar^2 L_a} \sum_n (E_F - E_n).$$

(3.14)
It is noted that $N_D$ expression is valid for summation over subband levels $E_n$ below the Fermi level $E_F$ and the approximate expression for $N_D$ is only true for cryogenic temperature.

As a result, in the cryogenic temperature range, the dark current from thermionic emission conduction is exponentially proportional to the doping concentration in the quantum well,

$$I_{th} \propto e^{E_F/(k_B T)} \propto e^{C N_D/(k_B T)}$$

(3.15)

where $C$ is a constant. It is noted that the dark current is a strong function of the quantum well doping concentration. On the other hand, the intersubband absorption is proportional to the well doping concentration. Therefore, the optimized QWIP performance is the tradeoff between the high intersubband transition and the low dark current operation.

In the miniband conduction, the coherent tunneling current component is dominant compared to the thermionic emission current component and other components such as sequential tunneling, phonon-assisted tunneling, and defect-assisted tunneling. The coherent tunneling current along the superlattice axis can be expressed by [50, 51]

$$I_{\text{tun}} = A_d \int_0^{\infty} |T \cdot T| g(E_z, V_b) dE_z$$

(3.16)

where $|T \cdot T|$ is the transmission probability (see Chapter 2.3.2) and $g(E_z, V_b)$ is the energy distribution function along superlattice axis at bias voltage $V_b$, which can be expressed as

$$g(E_z, V_b) = \frac{4\pi e m^*_e k_B T}{\hbar^3} \ln \left( \frac{1 + \exp[(E_F - E_z)/(k_B T)]}{1 + \exp[(E_F - E_z - eV_b)/(k_B T)]} \right).$$

(3.17)

Modified Fermi level $E_F$ resulting from the correction due to exchange energy, cryogenic temperature, depolarization effect should be used in the calculation of both $I_{th}$ and $I_{\text{tun}}$. 
3.4.2. Spectral Responsivity $R_A$

Spectral responsivity $R_A$ for the PC mode QWIP is defined by the photocurrent output (in ampere) under IR radiation power (in watt) at a specific wavelength. The responsivity depends on the detector quantum efficiency $\eta$ and the photoconductive gain $g$, and can be written as

$$R_A = \frac{e}{h \nu} (\eta \cdot g) = \frac{e}{h \nu} \eta_c \lambda$$

$$= \frac{\lambda}{1.24 \eta_c},$$

where

$$\eta = \kappa (1 - R_f) (1 - e^{-\alpha m})$$

Here $R_f$ is the reflection coefficient (typical 0.3 for GaAs), $\kappa$ is the polarization correction factor ($\kappa = 0.5$ for n-type QWIP and $\kappa = 1$ for p-type QWIP), $m$ is the number of absorption pass, $\alpha$ is the absorption coefficient for the superlattice, and $l$ is the total superlattice thickness.

The spectral responsivity (V/W) for the PV mode QWIP can be obtained from the relationship $R_V = R_A \cdot R_d$, where $R_d$ is differential resistance of a QWIP.

3.4.3. Collection Efficiency $\eta_c$

The QWIP collection efficiency $\eta_c$ describes the converting efficiency from incident radiation photons to net carriers that are collected at the output of the QWIP, and is defined as the product of the quantum efficiency $\eta$ to photoconductive gain $g$, namely, $\eta_c = \eta \cdot g$.

Photoconductive gain $g$ is expressed as the ratio of the carrier transport lifetime $\tau_L$ to the transit time $\tau_T$ through a QWIP. From the empirical point of view, the photoconductive gain can be described in terms of the capture or trapping probability $p_e$ [52, 53],

$$g = \frac{1 - p_e}{Np_e}$$

The trapping probability $p_e$ is defined as the ratio of the escaping time in the well region to the lifetime of the excited carriers from the confined ground state. If the
excited states are resonantly lined up with the top of the barrier, the escaping time will be greatly reduced, thus minimizing trapping probability and maximizing the photoconductive gain.

The final expression for $\eta_c$ can be given by

$$\eta_c = \kappa (1 - R_f) (1 - e^{-m_0}) \frac{1 - p_c}{N_p} \quad (3.22)$$

$$\approx \kappa (1 - R_f) \frac{m_0}{N_p} \quad (3.23)$$

It is noted that the approximate expression is only true for $m_0 \ll 1$ and $p_c \ll 1$.

3.4.4. Detectivity $D_\lambda^*$

The detectivity of a QWIP is a very important figure of merit, which measures the QWIP sensitivity and the normalized QWIP noise equivalent power (NEP) with respect to the detector area and noise bandwidth. It can be calculated by

$$D_\lambda^* = \frac{R_A \sqrt{A_d \Delta f}}{i_n}, \quad (3.24)$$

where $\Delta f$ is the noise spectral bandwidth, and $i_n$ is the overall root-mean-square noise current (in unit of A) for a QWIP. In general, the noise current for the QWIP includes two components, one is QWIP's dark current noise $i_{nd}$ and the other is 300 K background photon noise current $i_{nb}$.

The dark current noise $i_{nd}^2$ is given by

$$i_{nd}^2 = \begin{cases} 
4eI_d g \Delta f & \text{for G-R noise} \\
\frac{4k_B T}{R_d} \Delta f & \text{for Johnson noise.}
\end{cases} \quad (3.25)$$

The G-R noise is associated with random thermal excitation and decay of the carriers, thus resulting in the fluctuation in the number of the carriers in the QWIP. The G-R noise is the dominant noise current source in the PC mode detection QWIP. However, the Johnson noise is associated with the fluctuation in the velocity of the carriers, which is the dominant noise current source in the PV mode detection QWIP.

The background photon noise is caused by the fluctuations in the number of background photons absorbed by a QWIP, which can be calculated based on the
arrival statistics of the incoherent photons. The background photon noise current $i_{nb}^2$ is given by [54, 55]

$$i_{nb}^2 = 4e^2 g^2 \left( \eta \kappa \frac{P_b}{h \nu} \right) B,$$

(3.26)

where $P_b$ is the incident background optical power for unit time, $B$ is the QWIP bandwidth, $\eta$ is the absorption quantum efficiency, $\kappa$ is the polarization correction factor, $\nu$ is the incident photon frequency, and $g$ is the photoconductive gain.

The overall noise current for the QWIP is expressed by

$$i_n^2 = i_{nd}^2 + i_{nb}^2$$

(3.27)

and

$$i_n^2 = 4eg \left[ I_d + eg \left( \eta \kappa \frac{P_b}{h \nu} \right) \right] \Delta f$$

(3.28)

and

$$i_n^2 = 4eg(I_d + I_b) \Delta f,$$

(3.29)

where $I_b = eg\eta\kappa[P_b/(h\nu)]$ is the background photocurrent detected by the QWIP. When $I_d < I_b$, the overall noise current $i_n \sim i_{nb}$, and the QWIP is operated under the background photon noise limitation. When $I_d > I_b$, the overall noise current $i_n \sim i_{nd}$ and the QWIP is operated under the operation of G-R noise or Johnson noise limitation. The detectivity $D^*_\lambda$ for each noise source limitation can be calculated by

$$D^*_\lambda = \begin{cases} \frac{\kappa R_A \sqrt{A_d \Delta f}}{i_{nb}} & \text{for background photon noise limitation} \\ \frac{R_A \sqrt{A_d \Delta f}}{i_{nd}} & \text{for dark current noise limitation.} \end{cases}$$

(3.30)

3.4.5. Background Limited Performance (BLIP)

A mid-wavelength or long-wavelength QWIP has two kinds of backgrounds: (1) high temperature ambient background ($T = 300$ K) and (2) low temperature cold background ($T = 77$ or 195 K). Under the normal thermal imaging condition, the total current feeding to the following readout circuits in a QWIP includes both the dark current $I_d$ and 300 K background photocurrent $I_b$ (i.e., $I_d + I_b$). Due to the limitation on the charge handling capacity in the following readout circuits, the total current level of a QWIP under proper operation must be below this limited charge capacity for a given integration time of the imaging arrays. In addition, in order to achieve
the stable and clear imaging patterns, it is highly desirable to operate QWIPs under the background photon noise limitation, that is the background limited performance (BLIP).

The BLIP operation requires that $I_b > I_d$. In order to reduce $I_d$ down to less than $I_b$, QWIP has to be operated at a low temperature $T \sim 77$ K for LWIR (8 ~ 14 $\mu$m) detection and $T \sim 195$ K for MWIR (3 ~ 5 $\mu$m) detection. BLIP temperature $T_{\text{BLIP}}$ can be found from

$$I_d(T = T_{\text{BLIP}}) = I_b$$

$$= e g \eta \kappa \left( \frac{P_b}{h \nu} \right)$$

$$= A_d e g \eta \kappa Q_b$$

(3.31)

(3.32)

(3.33)

where $Q_b = P_b/(A_d h \nu)$ is the incident photon flux density from the background for a given spectral bandwidth $\Delta \nu$ at peak wavelength $\lambda_p$. $Q_b$ is given by

$$Q_b = \frac{2\pi}{c^2} \frac{\nu^2 \Delta \nu}{e h \nu/k_B T_B - 1} \sin^2 \left( \frac{\theta}{2} \right),$$

(3.34)

where $\theta$ is the field of view (FOV) and $T_B$ is the background temperature of the QWIPs ($T_B = 300$ K for ambient temperature). On the other hand, the background photocurrent $I_b$ can be modified by using different FOV. As a result, $T_{\text{BLIP}}$ for a QWIP can also be changed by using different FOV optical configuration.

In a BLIP QWIP, the dominant noise source is the background photon noise while other noise sources such as G-R noise and Johnson noise are negligible in comparison. Under normal imaging conditions, the photosignal current $I_{ph}$ can be approximated by

$$I_{ph} = (e/h \nu) \eta \kappa g P_{ph},$$

(3.35)

where $P_{ph}$ is the incident optical signal power for the unit time. By setting the signal-to-noise power ratio equal to unity (i.e., $I_{ph} = i_{nb}$), the background-limited noise equivalent power (NEP)BLIP and the detectivity $D^*_\text{BLIP}$ for the QWIPs can be
expressed by

\[
(NEP)_{BLIP} = 2\sqrt{\hbar \nu BP_b/(\eta \kappa)},
\]

\[
D_{BLIP} = \sqrt{A_d B/(NEP)_{BLIP}} = \frac{\lambda}{2\hbar c} \left( \frac{\eta \kappa}{Q_h} \right)^{1/2}.
\]

(3.36) (3.37)

It is noted that the detectivity \(D_{BLIP}^*\) for the BLIP QWIP is independent of both photoconductive gain \(g\) and dark current \(I_d\), while the detectivity for the non-BLIP QWIP is dependent of both the \(g\) and the \(I_d\).

When the readout circuit noise is ignored, \%BLIP for a QWIP can be evaluated by using

\[
\%BLIP \approx \frac{i_{nb}}{(i_{nb}^2 + i_{nd}^2)^{1/2}}
\]

(3.38)

where \(i_{nb}\) and \(i_{nd}\) are the 300 K background photocurrent noise and dark current noise, respectively.
CHAPTER 4
A DUAL-MODE PC AND PV GaAs/AlGaAs QUANTUM WELL
INFRARED PHOTODETECTOR (DM-QWIP)
WITH TWO-COLOR DETECTION

4.1. Introduction

Recently, there has been considerable interest in the study of long-wavelength intersubband quantum well infrared photodetectors (QWIPs). A great deal of work has been reported on the lattice-matched GaAs/AlGaAs and InGaAs/InAlAs multiple quantum well and superlattice systems using bound-to-bound [20], bound-to-miniband (BTM) [14], and bound-to-continuum [12] intersubband transitions. Although a majority of the study on intersubband absorption has been based on the photoconductive (PC) mode operation [56], studies of the photovoltaic (PV) mode operation have also been reported in the literatures [17, 19, 23, 57]. However, due to the relatively low detectivity in these PV mode QWIPs, they have to be operated below 77 K to reduce the Johnson noise. Therefore, improvement of the performance in PV mode QWIPs is highly desirable for large area focal plane array (FPA) image sensor applications.

4.2. Design Consideration

A new GaAs/AlGaAs dual-mode (PC and PV) quantum well infrared photodetectors (DM-QWIP) based on bound-to-continuum state transition mechanism was designed and fabricated [58]. Both PC and PV detection modes for this QWIP can be operated at 77 K with excellent characteristics. By properly selecting the detector parameters, we tuned the PV and PC mode operations to the different response peak wavelengths. The DM-QWIP layer structure was grown on a semi-insulating (SI)
GaAs substrate by using the molecular beam epitaxy (MBE) technique. A 1-\(\mu m\)-thick GaAs buffer layer with dopant density of \(2\times10^{18}\) cm\(^{-3}\) was first grown on the SI GaAs substrate as an ohmic contact layer, followed by the growth of 40 periods of enlarged GaAs quantum well with well width of 110 Å and a dopant density of \(5\times10^{18}\) cm\(^{-3}\). The enlarged barrier layer on each side of the GaAs quantum well consists of an undoped Al\(_{0.25}\)Ga\(_{0.75}\)As (875 Å) layers. Finally, a \(n^+\)-GaAs cap layer of 0.45 \(\mu m\) and a dopant density of \(2\times10^{18}\) cm\(^{-3}\) was grown on top of the QWIP layer structure to facilitate ohmic contact. The physical parameters of the device structure are chosen so that there are two bound states inside the enlarged well (i.e. \(E_{EW0}\) and \(E_{EW1}\)), and the continuum states \(E_{CN}\) are just slightly above the top of the barrier. A high dopant density of \(5\times10^{18}\) cm\(^{-3}\) was used in the enlarged GaAs quantum well so that the ground state \(E_{EW0}\) and the first excited state \(E_{EW1}\) are heavily populated by electrons to enhance absorption of infrared radiation in the quantum well. In order to minimize the undesirable tunneling current through the barrier layers, a thick (875 Å) undoped Al\(_{0.25}\)Ga\(_{0.75}\)As barrier layer was used in this QWIP structure to suppress the tunneling current from the ground state \(E_{EW0}\) and the first excited state \(E_{EW1}\).

Figure 4.1 (a) shows the energy band diagram of the DM-QWIP, which illustrates the Fermi-level and two possible intersubband transition schemes. The first transition scheme is from the localized ground state \(E_{EW0}\) in the GaAs quantum well to the first continuum band states \(E_{CN}\) above the AlGaAs barrier. The second transition scheme takes place from the first excited state \(E_{EW1}\) to the continuum states \(E_{CN}\). Due to the dopant migration into the enlarged AlGaAs barriers from the heavily doped GaAs quantum well during the layer growth, the actual conduction band diagram in the DM-QWIP is shown in Fig 4.1 (b). The asymmetric band bending between two side of the quantum wells induces the internal electric field \(E_{\text{i}}\), which is opposite to the direction of the quantum well layer growth. To analyze these transition schemes, we performed theoretical calculations of the energy levels of the bound states and
continuum states and transmission probability $|T \cdot T|$ for this QWIP using a multilayer transfer matrix method [14] and the results are shown in Fig. 4.2. It is noted that the tunneling probability from the ground states and first excited state through the barrier layers are dramatically reduced so that the tunneling current is virtually eliminated. In order to precisely determine the intersubband transition levels, a complex calculation of the energy difference between the subband levels in the DM-QWIP should be performed. These include considerations of band nonparabolicity [39], electron-electron interaction [35], electron plasma [37], and energy band bending effect [40]. For simplicity, we have only considered the effects due to energy bending, depolarization, and electron-electron interaction in heavily doped bound states in the quantum well. By taking these effects into account, both bound states $E_{EW0}$ and $E_{EW1}$ are lowered by about $\sim 5$ meV. Thus two intersubband transition peaks should be observed in the DM-QWIP, which corresponds to infrared wavelengths of 7.7 $\mu$m and 12 $\mu$m. Due to the thick barrier layers used in this QWIP, only thermal- and photoexcited electrons can be transported through the continuum states above the barrier and collected by the external ohmic contacts. As a result, charges separation occurs under the internal electric field $E_{bi}$, which leads to the creation of a potential difference between the two ohmic contacts of the detector. Furthermore, an asymmetrical energy band bending due to heavy doping effect can also promote the creation of internal photovoltage under IR illumination.

4.3. Experiments

The DM-QWIP mesa structure was created by chemical etching through the quantum well active layers and stopped at the 1-$\mu$m-thick heavily doped GaAs buffer layer for ohmic contact. The active area of the detector is 200×200 $\mu$m$^2$. To enhance the normal incidence coupling efficiency in the quantum well, we apply a planar metal grating coupler on the top of detector for normal illumination. The planar metal grating coupler consists of regularly spaced metal grating strips of 0.2 $\mu$m thickness
and was deposited by using electron beam (E-beam) evaporation of AuGe/Ni/Au materials. To achieve high coupling efficiency, the metal grating strips with a grating periodicity of \( \Lambda = 5 \, \mu m \) and ratio factor \( d/\Lambda = 0.5 \) (d: the metal strip width) were used in this DM-QWIP.

The infrared intersubband absorption spectra of the sample were measured at the Brewster angle \( (\theta_B \approx 73^\circ) \) by using a Bruker Fourier transform interferometer (FTIR) at room temperature. The directly measured quantity is the absorbance \( A = -\log_{10}(\text{transmission}) \), which can be converted to the absorption coefficient \( \alpha \) for 45\(^\circ\) incident value. The main lobe of absorption coefficient for incident of 45\(^\circ\) is shown in Fig. 4.3. It is noted that main absorption peak is centered at \( \lambda_p = 12.3 \, \mu m \).

Figure 4.4 shows the current-voltage (I-V) curves and the differential resistance \( R_d \) values for the DM-QWIP measured at negative bias and \( T = 77K \) (mesa top as positive bias). It is noted that the dark current for bias voltage between -1 and -2 V is extremely low, which is attributed to the dramatically reduced tunneling current resulting from the increase of barrier layer thickness. Asymmetric dark current characteristics was observed in the DM-QWIP with a higher current in positive bias than that in negative bias, which results from the asymmetric effective barrier height at different polarity of applied bias as shown in Fig. 4.5. The photocurrent was measured as a function of temperature, bias voltage, polarization direction, and wavelength, using an ORIEL 77250 single grating monochromator and ceramic element infrared source. Figure 4.6 shows a plot of the normalized responsivity versus wavelength for the QWIP measured at \( T = 77 \, K \). Two responsivity peaks were observed: one at \( \lambda_p = 7.7 \, \mu m \) and \( V_b = 0 \, V \), and the other at \( \lambda_p = 12 \, \mu m \) and \( V_b > -1 \, V \). At zero bias condition, the detector operates in the PV detection mode with a peak photovoltage responsivity \( R_V = 11,000 \, V/W \) at \( \lambda_p = 7.7 \, \mu m \), which is attributed to the ground state \( E_{EW0} \) to the first continuum state \( E_{CN} \) transition above the barrier. The photoexcited carriers are driven by the internal \( V_{bi} \) (or \( E_{bi} \)) to generate a PV response.
current from the top of mesa to the bottom. At $T = 77$ K, the zero bias differential resistance was found to be $R_d = 5.5$ MΩ at $T = 77$ K. Since the detector operating in the PV mode is limited by Johnson noise (i.e. $i_n = \sqrt{4k_BT\Delta f/R_d}$), the detectivity $D_A^*$ for the PV mode was found to be $1.5\times10^9$ cm-$\sqrt{Hz/W}$. In order to verify the zero bias noise, we also measured the noise current by using a lock-in amplifier, which yielded a value of $i_n = 3.0\times10^{-14}$ A, in good agreement with the calculated value from Johnson noise expression. When a negative bias voltage $V_b$ is applied to the detector that is opposite to the $V_m$, the PV response vanishes, and the PC mode conduction becomes the dominant detection mechanism with a PC response current from the bottom of the mesa to the top. The bias dependence of the photocurrent responsivity $R_A$ was measured using a 12 $\mu$m IR radiation at $T = 77$ K, and the result is shown Fig. 4.7. The maximum responsivity $R_A$ was found to be $0.48$ A/W at $V_b = -2$ V and $T = 77$ K. As expected, the detector responsivity $R_A$ increases with the applied bias voltage from $V_b = -1$ V to $V_b = -2$ V. For $V_b > -2$ V, the photocurrent becomes saturated. The cutoff wavelength for this detector was found to be $\lambda_c = 13.2$ $\mu$m with a spectral bandwidth $\Delta\lambda/\lambda_p$ of 18.3 %.

From the measured responsivity and dark current, we can calculate the detectivity $D_A^*$ of the detector using formula, $D_A^* = R_A(A_d\Delta f)^{1/2}/i_n$, where $A_d$ is the effective area of the detector and $\Delta f$ is the noise bandwidth. The dark current G-R noise $i_n$ is given by $i_n = \sqrt{4eI_dg\Delta f}$ and may be evaluated from the measured responsivity $R_A = (\lambda/1.24)(\eta g)$ and the unpolarized quantum efficiency expression $\eta = (1/2)(1-e^{-2\alpha})$. The photoconductive gain, $g$, can be also derived from noise measurement. The results yielded a peak detectivity $D_A^* = 2\times10^{10}$ cm-$\sqrt{Hz/W}$ at $\lambda_p = 12$ $\mu$m and $T = 77$ K for the PC mode operation. As shown in Fig. 4.7, the value of $D_A^*$ decreases with increasing negative bias voltage.
4.4. Conclusions

In conclusion, we have demonstrated a new high performance PC and PV dual-mode operation GaAs QWIP using transition from the highly populated ground state and first excited state in the enlarged GaAs quantum well to the continuum band states above the AlGaAs barrier. The two bound states confined in the quantum well are a result of using the enlarged quantum well structure in the GaAs/AlGaAs DM-QWIP. With high detectivity and low dark current for both the PC and PV mode IR detection, the GaAs/AlGaAs DM-QWIP can be used for high performance two-color and dual-mode operation staring focal planar arrays and infrared imaging sensor applications.
Figure 4.1. Schematic energy-band diagram for a GaAs/AlGaAs DM-QWIP structure, (a) ideal case and (b) asymmetric energy-band bending which is a result of dopant migration effect in the quantum well. An internal electric field $E_{bi}$ is generated within the QWIP structure, which is opposite to the growth direction of the QWIP.
Figure 4.2. Calculated energy states and transmission coefficient $|T\cdot T|$ for the GaAs/AlGaAs DM-QWIP structure by using a multiple-layer transfer matrix method.
Figure 4.3. Measured intersubband absorption coefficient (converted to 45° incident values) by Bruker FTIR at the Brewster angle and $T = 300$ K.
Figure 4.4. Dark current and differential resistance versus applied bias for the GaAs/AlGaAs DM-QWIP at $T = 77$ K.
Figure 4.5. Effective barrier height seen by excited carriers for (a) zero bias, (b) reverse bias, and (c) forward bias. It is noticed that the effective barrier height is higher in reverse bias than in forward bias.
Figure 4.6. Relative responsivity versus wavelength for the GaAs/AlGaAs DM-QWIP at $T = 77$ K.
Figure 4.7. Responsivity and detectivity versus applied bias at $\lambda_p = 12 \mu m$ and $T = 77 K$ for the GaAs/AlGaAs DM-QWIP.
5.1. Introduction

Long-wavelength quantum well infrared photodetectors (QWIPs) based on intersubband transitions for detection in the 8-14 μm atmospheric spectral window have been extensively investigated in recent years. Studies of the intersubband absorption in the InGaAs/InAlAs system for 3 to 5 μm and 8 to 14 μm detection have also been reported [18, 59]. Since the InGaAs/InAlAs heterostructure has a large conduction band offset (ΔEc ~ 500 meV) compared to GaAs/AlGaAs system, it is a promising candidate for both the mid-wavelength infrared (MWIR) and the long-wavelength infrared (LWIR) applications. Recently, we have reported the observation of a largely enhanced intersubband absorption in the InAlAs/InGaAs system using intersubband transition for 8-14 μm [59] wavelength detection. The result showed multi-color infrared detection can be realized in the InGaAs/InAlAs QWIP due to a much large potential barrier created by using a short period superlattice barrier structure and resonant miniband conduction mechanism.

5.2. Design Consideration

A dual-mode (PV and PC) operation InGaAs/InAlAs QWIP [45] based on the voltage-tuned (VT) bound-to-miniband (BTM) transition mechanism was designed and fabricated. The VT-QWIP layer structure was grown on a semi-insulating (SI) InP substrate by using the molecular beam epitaxy (MBE) technique. A 1-μm In0.53Ga0.47As buffer layer with dopant density of 2×10¹⁸ cm⁻³ was first grown on
the SI InP substrate, followed by the growth of 20 periods of enlarged In_{0.53}Ga_{0.47}As quantum wells with a well width of 110 Å and a dopant density of 5×10^{17} \text{ cm}^{-3}. The barrier layers on each side of the quantum well consist of 6 periods of undoped In_{0.52}Al_{0.48}As (35 Å)/In_{0.53}Ga_{0.47}As (50 Å) superlattice layers. A 0.3-μm-thick n⁺-In_{0.53}Ga_{0.47}As cap layer with a dopant density of 2×10^{18} \text{ cm}^{-3} was grown on top of the VT-QWIP layer structure to facilitate the ohmic contact. Figure 5.1 shows the energy band diagram for this VT-QWIP. The transition scheme is from the localized ground state level E_{EW1} of the enlarged well (EW) to the global resonant-coupled miniband E_{SL1} in the superlattice (SL) barrier. The physical parameters of the quantum well and superlattices are chosen so that the first excited level E_{EW2} of the EW is merged and lined up with the ground miniband E_{SL1} of the SL on both sides of the quantum well to obtain a maximum intersubband absorption strength.

To analyze these bound-to-miniband transition schemes, theoretical calculations of the energy states E_{EWn}, E_{SLn} (n = 1,2,...) and the transmission probability |T · T| for the VT-QWIP were carried out by using the multi-layer transfer matrix method. In this design, a broad and highly degenerated miniband was formed by using the superlattice barrier structure. The center energy position of the first miniband is located at 163 meV above the conduction band edge of InGaAs EW with a bandwidth of \Gamma \sim 60 \text{ meV}. In order to precisely determine the intersubband transition levels, we have considered both the electron-electron interaction (exchange energy) E_{exch} and depolarization E_{dep} effects. The results show a lowering of \sim 5 \text{ meV} for the heavily populated bound states E_{EW1} in the quantum well. The peak absorption wavelength can be found from the relation,

$$\lambda_p = \frac{1.24}{E_{SL1} - E_{EW1} + E_{exch} - E_{dep}} (\mu\text{m}).$$  (5.1)

Now, substituting values of E_{SL1} = 163 \text{ meV}, E_{EW1} = 51 \text{ meV}, and E_{exch} - E_{dep} \sim 5 \text{ meV} into the above equation, we obtain \lambda_p = 10.6 \mu\text{m}. The infrared intersubband absorption versus wavelength for the VT-QWIP was measured at the Brewster angle
(θB ≈ 73°) by using a Perkin-Elmer Fourier transform interferometer (FTIR) at room temperature [59]. The results showed a main absorption peak centered at λp = 10.7 μm with a spectral linewidth of Δν = 500 cm⁻¹.

5.3. Experiments

The mesa structure for the VT-QWIP was formed by chemical etching through the QWIP active layers and stopped at the n⁺ InGaAs buffer layer for ohmic contact. The active area of the detector is 200×200 μm². To enhance coupling efficiency for normal illumination and angular-independent radiation polarization, a planar two-dimensional (2-D) metal grating coupler was formed on the VT-QWIP by using electron beam (E-beam) evaporation of 0.2 μm gold films. The metal grating coupler consists of equally spaced square shape metal grating with a grating periodicity of Λ = 10 μm and a geometrical ratio factor d/Λ = 0.5, where d is the width of the square metal grating.

Figure 5.2 shows the dark current-voltage (I-V) and the differential resistance (Rd) curves for the QWIP measured at T = 67 K. Asymmetric dark current characteristics was observed in the QWIP (mesa top as positive bias). The photocurrent was measured as a function of temperature, bias voltage, polarization direction, and wavelength using an ORIEL 77250 single grating monochromator and ceramic element infrared source. Figure 5.3 shows the normalized responsivity versus wavelength measured at Vb = 0, - 0.5 V and T = 67 K. In the PV mode operation (Vb = 0 V), the detector has a peak wavelength response at λp = 10 μm with a cutoff wavelength λc = 10.4 μm. When a negative voltage is applied to the QWIP, the PC mode conduction becomes the dominant conduction mechanism. The peak wavelength λp for the PC mode detection was found to be at λp = 10.3 μm, while a full width at half maximum of Δν = 232 cm⁻¹ (∼ 29 meV) was obtained from Fig. 5.3. The bandwidth Δλ/λp = 24 % from PC mode response curve was found to be much narrower than the room temperature FTIR absorption curve [59]. The intersubband transitions of both the
PC mode and PV mode are attributed to the energy resonant transition from the ground state $E_{EW1}$ to the global miniband $E_{SL1}$ states which are aligned with the first excited state $E_{EW2}$ in the quantum well. The intersubband resonant transition (maximum absorption strength or maximum wavefunction overlap) depends strongly on the location of the first excited state $E_{EW2}$ of the quantum well relative to the miniband edges, $E_{SL1}$ [16]. In the VT-QWIP structure, the $E_{EW2}$ lies near the top of the miniband edges $E_{SL1}$, which results in a strong, blueshift (0.7 $\mu$m compared with room temperature FTIR peak wavelength 10.7 $\mu$m), and narrow-band spectral response in the PV mode detection with a linewidth of $\Delta \lambda = 0.7$ $\mu$m at a half maximum. The bound-to-miniband transition QWIP operated in the PV mode offers a unique feature of ultra-narrow bandwidth ($\Delta \lambda / \lambda_p = 7$ %) infrared detection, which is not attainable in a conventional bound-to-continuum QWIP. As the negative bias increases, relative position between the “embedding” state $E_{EW2}$ and the “framing” state $E_{SL1}$ can be adjusted by the “controlling bias” due to the different dependence of $E_{EW2}$ and $E_{SL1}$ on the bias voltage. A peak wavelength blueshift of about 0.4 $\mu$m (compared with the FTIR peak wavelength) was observed at $V_b = -0.5$ V and $T = 67K$. As expected, a broad-band spectral linewidth of $\Delta \lambda / \lambda_p = 24$ % at $V_b = -0.5$ V was obtained in the PC mode as shown in Fig. 5.3. It is notice that 0.3 $\mu$m peak wavelength shift between the PC mode and PV mode operation was obtained by the applied bias. In the bias-tuned QWIP structure, not only can the spectral bandwidth be tailored to the desired width (from 7 % to 24 %), but the spectral response peak can also be tuned as well. This tunability can be obtained by modulating the relative position of the first excited bound state in the quantum well within miniband states. For example, if the first bound excited state lies at the bottom edge of the miniband, then the spectral response will produce a redshift with a longer short-wavelength tail and narrow bandwidth. On the other hand, if the first bound excited state lies at the top of the miniband, then a blueshift results with a longer long-wavelength tail and
narrow bandwidth. However, if the first excited state is in the middle of the miniband, then a broader photoresponse curve is expected. This tunability is illustrated in Fig. 5.4.

The photocurrent responsivities $R_A$ of the PC mode and PV mode operation were measured at $T = 67$ K, $\lambda_p = 10.3$ $\mu$m and 10 $\mu$m, respectively, and results are shown in Fig. 5.5. The peak responsivity for PV mode was found to be 12,000 V/W at 10 $\mu$m. The photocurrent responsivity $R_A$ for the PC mode, measured at $V_b = -0.5, -1.5$ V, was found to be 38 mA/W, 145 mA/W, respectively.

5.4. Results and Discussion

The detectivity $D*A$ can be calculated from the measured responsivity and dark current. Photoconductive gain can be also derived from the noise measurement. The results yielded a peak detectivity $D*A = 5.8 \times 10^9$ cm-$\sqrt{Hz}$/W at $\lambda_p = 10.3$ $\mu$m, $V_b = -0.5$ V, and $T = 67$ K for the PC mode operation. As shown in Fig. 5.5, the value of $D*A$ decreases with increasing negative bias $V_b$ due to the increase of dark current with increasing the bias voltage. The zero bias differential resistance $R_d$ was found to be about 450 K$\Omega$ at $T = 67$ K. Since the detector operating in the PV mode is limited by Johnson noise, the detectivity $D*A$ for the PV mode was found to be $5.7 \times 10^9$ cm-$\sqrt{Hz}$/W. In order to verify the zero bias noise, we also measured the noise current by using a lock-in amplifier, which yielded a value of $i_n = 9.0 \times 10^{-14}$ A, in good agreement with the calculated value from the Johnson noise expression.

Due to the dopant migration into superlattice barriers from the doped quantum wells, an internal built-in electric field $E_{bi}$ is generated with the direction opposite to the QWIP layer growth direction. Schematic energy band diagram of considering the dopant migration effect is illustrated in the Fig. 5.6. The miniband bandwidth on two side of each quantum well was modified by the existence of the $E_{bi}$ (so called miniband bandwidth modulation (MBM)). As a result, bandwidth of the global miniband becomes spatially nonuniform with broadening on the well right-hand side and
narrowing on the left-hand side as shown in the Fig. 5.6. The 15 meV wider miniband bandwidth on the side of toward-growth-direction of each InGaAs well than that on the side of backward-growth-direction can be identified and confirmed by temperature-dependent dark I-V and photocurrent measurements. For $V_b < -0.15$ V, the photoresponse at $\lambda_p = 10.3$ $\mu$m decreases with increasing bias voltage, indicating that the internal photovoltage is offset by the applied bias voltage in this bias range. For $V_b > -0.15$ V, the response starts to increase again, which implies that the PC mode conduction will take over when applied bias exceeds the built-in potential $V_{bi} \sim +0.15$ V resulting from miniband bandwidth modulation. The built-in electric field $E_{bi}$ is estimated to be about $2.0 \times 10^3$ V/cm, which is slightly below the electric field $E_p = 3 \times 10^3$ V/cm for the peak value of electron drift velocity $v_d$. Since tunneling time constant $\tau_o$ is inversely proportional to the miniband bandwidth $\Gamma (\tau_o = \hbar/\Gamma)$, the tunneling probability of the photoexcited carriers is 40 % higher toward growth direction than backward growth direction. This different carrier tunneling probability resulting from the MBM gives rise to the PV mode detection.

5.5. Conclusions

In conclusion, we have demonstrated a new high performance PV and PC dual-mode operation InGaAs/InAlAs QWIP using voltage-tuned bound-to-miniband transition mechanism. Both the narrow-band PV mode and broad-band PC mode detection at $\lambda_p \sim 10$ $\mu$m peak wavelength have been achieved. Using the dual-mode operation and bound-to-miniband transition InGaAs/InAlAs QWIP structure grown on the InP substrate, it is possible to design high performance two-color staring focal plane arrays and infrared imaging sensor for use in the 3-5 $\mu$m and 8-14 $\mu$m detection.
$\Delta E_c = 500$ meV

Figure 5.1. Schematic energy band diagram showing the intersubband transitions from the ground state $E_{EW1}$ to the miniband states $E_{SL1}$. The relative position of the first excited state $E_{EW2}$ to miniband edges strongly influences the resonant intersubband transition [16].
Figure 5.2. Dark current and differential resistance versus applied bias for the InGaAs/InAlAs QWIP measured at $T = 67$ K.
Figure 5.3. Relative responsivity versus wavelength for the InGaAs/InAlAs QWIP measured at $T = 67$ K.
Figure 5.4. Relative spectral response versus wavelength for VT-QWIP (a) $E_{EW2}$ lined up at the top of the $E_{SL1}$ miniband states (blueshift), (b) $E_{EW2}$ in the center of the $E_{SL1}$ miniband states (broad bandwidth), and (c) $E_{EW2}$ at the bottom of the $E_{SL1}$ (redshift).
Figure 5.5. Responsivity and detectivity versus applied bias $V_b$ at $\lambda_p = 10.3 \, \mu m$ and $T = 67 \, K$. 
Figure 5.6. Modified energy band diagram at zero bias. An internal electric field $E_{bi}$ is generated in the VT-QWIP, and a modulation miniband bandwidth is formed with tunneling time constant to the left-hand side larger than that to the right-hand side, $\tau_\text{o(left)} > \tau_\text{o(right)}$. 
6.1. Introduction

Quantum well infrared photodetectors (QWIPs) using the intersubband optical transitions for detection in the 3 - 5 \( \mu \text{m} \) and 8 - 14 \( \mu \text{m} \) have been explored in recent years. Most of the III-V QWIPs have been fabricated from the MBE grown GaAs/AlGaAs and InGaAs/InAlAs material systems using the bound-to-bound [11, 20, 60, 61], bound-to-miniband (BTM) [14, 16, 62] and bound-to-continuum [12, 18, 22] conduction intersubband transitions and operating on photoconductive (PC) detection scheme. Although a majority of the studies on the intersubband absorption has been based on the PC mode operation, studies of the photovoltaic (PV) mode [23, 63, 64] and dual-mode (PV & PC modes) [45, 58] operation have also been reported recently. Since the PV detection mode is operated under zero-bias condition, it has the advantages of lower dark current and lower noise equivalent power compared to PC mode operation.

Since the quality of the interfaces between the quantum well and the barrier layer is extremely important for the fabrication of high performance QWIP, most of the III-V QWIPs reported in the literature are grown by using molecular beam epitaxy (MBE) technique. Recently, several reports have shown [65, 66, 67] that metal-organic chemical vapor deposition (MOCVD) technique is well adapted to the growth of a lattice-matched GaAs/In\(_{1-x}\)Ga\(_x\)P material system which has a number of advantages over the AlGaAs/GaAs material system [68, 69]. The main features of this material system include, (1) selective chemical etching between InGaP and GaAs in addition to less surface oxidation during device fabrication process, (2) less
degradation of device performance due to the absence of aluminum, (3) low growth temperature which makes this material compatible with monolithic integration for optoelectronic integrated circuits [70, 71], (4) high crossover of the direct and indirect conduction bands at \( x = 0.74 \), therefore, far away from the composition lattice-matched to GaAs \( (x = 0.51) \), which allows operation without significant donor-related DX center problem and interface defect-assisted tunneling, (5) extremely high electron mobility in this heterostructure [72] system, and (6) ultra low recombination velocity [73] at its heterostructure interfaces. The lattice-matched GaAs/In\(_{0.49}\)Ga\(_{0.51}\)P system has been used in quantum wells and superlattices for electronic and photonic devices such as high electron mobility transistors (HEMTs) [70, 71], heterojunction bipolar transistors (HBTs) [74], lasers [67], light-emitting diodes [75], and photodiodes [65].

A new photovoltaic (PV) mode operation long wavelength quantum well infrared photodetector (QWIP) using a lattice-matched n-type GaAs/In\(_{0.49}\)Ga\(_{0.51}\)P system has been demonstrated for two-color IR detection. The detection scheme is based on bound-to-continuum states transitions from the ground bound state inside the GaAs quantum well to the first- and second-continuum band states above the InGaP barrier. The peak photovoltaic responsivities were found to be 1,000 V/W and 900 V/W at \( \lambda_{p1} = 8.2 \, \mu m \) and \( \lambda_{p2} = 6.0 \, \mu m \) and \( T = 77 \, K \), respectively. The spectral response bandwidths corresponding to these two peak wavelengths were found to be 11 % and 13 %, respectively.

6.2. Design Consideration

A two-color PV mode operation QWIP fabricated on the GaAs/In\(_{0.49}\)Ga\(_{0.51}\)P material system was grown on an undoped GaAs substrate by using MOCVD technique. Trimethylindium (TMI) and triethylgallium (TEG) were used as indium and gallium sources, and arsine (AsH\(_3\)) and phosphine (PH\(_3\)) were used as arsenic and phosphorus sources. In order to obtain an high quality heterointerface, an 11-second interrupt growth between different layers was carried out at a substrate temperature
of 550 °C. A 0.7-μm GaAs buffer layer with sulphur (S) dopant density of $1 \times 10^{18}$ cm$^{-3}$ was first grown on the GaAs substrate as the ohmic contact layer, followed by the growth of a 15-period of GaAs quantum wells with a well width of 50 Å and a sulphur dopant density of $5 \times 10^{17}$ cm$^{-3}$. The barrier layers on each side of the GaAs quantum well consist of an undoped $In_{0.49}Ga_{0.51}P$ (360 Å) layer. Finally, a GaAs cap layer of 1 μm thick and a sulphur dopant density of $1 \times 10^{18}$ cm$^{-3}$ was grown on top of the QWIP layers to facilitate the top ohmic contact. The physical parameters of the QWIP are chosen so that only one electron populated bound state is located inside the quantum well and the first excited band states are just slightly above the top of the barrier layers in such a way to enhance the intersubband absorption strength. To analyze the transition schemes for this QWIP, we performed theoretical calculations of the energy levels of the bound state and the continuum states and transmission probability $|T \cdot T|$ for the QWIP using multilayer transfer matrix method [14, 62]. In this calculation, we have used a conduction band offset $\Delta E_c = 220$ meV and an electron effective mass $m^* = 0.1 m_0$ for the InGaP [76]. The calculated energy levels for the ground state is $E_0 = 75$ meV in the well, the first continuum state $E_1 = 221$ meV, and the second continuum state $E_2 = 300$ meV from the bottom of the quantum well. This design leads to a resonant absorption, hence maximizing the absorption strength in this QWIP. As a result, two absorption peaks at about 8.5 μm and 5.5 μm wavelengths from the intersubband transitions are expected from this QWIP. Although the effects of band nonparabolicity, electron-electron interaction, and electron plasma are responsible for modifying the transition energy levels, the energy band bending resulted from the sulphur dopant migration in the quantum wells to the InGaP barrier layers plays an important role in the PV intersubband detection. Figure 6.1 shows the energy band diagram based on the dopant migration model and intersubband transition probability calculated from the multilayer transfer matrix method. The asymmetric energy barrier at quantum well/barrier layer interfaces causes a built-in
potential distribution [58], and hence gives rise to the photovoltaic effect. In addition, the interface scattering process also leads to a preferential escape direction of the photoexcited carriers [63], which can enhance the photovoltaic detection in the QWIP.

6.3. Experiments

The mesa structure for the QWIP was formed by the chemical etching through the quantum well active layers using HCl:H₃PO₄ (1:1) for the InGaP barrier layers, and H₃PO₄:H₂O₂:H₂O (1:1:8) for the GaAs well layers. Au-Ge/Ni/Au ohmic contact films were deposited on the top and bottom contact layers. The active area of the detector is 200×200 μm². To enhance the coupling efficiency for normal illumination and angular independent radiation polarization, a planar 2-D metal grating coupler was formed on the QWIP top surface by using electron beam (E-beam) evaporation of 0.2 μm gold film. The 2-D metal grating coupler consists of equally spaced square shape metals with a periodicity of Λ = 10 μm and a geometrical ratio factor g = d/Λ = 0.5, where d is the width of the square shape metal grating.

Figure 6.2 shows the dark current-voltage (I-V) curves measured at room temperature. It is interesting to note that a Schottky diode characteristic with a turn-on voltage ~ 220 mV was observed at room temperature. The high resistance property observed in this GaAs/InGaP QWIP compared to the conventional GaAs/AlGaAs and InGaAs/InAlAs QWIPs may attribute to the effects of sulphur dopant migration into InGaP barrier layers, which makes InGaP barrier layers showing persistent photoconductivity [70]. Meanwhile, the high resistance is also related to the sulphur dopant loss during the sample growth due to its high diffusivity. The photocurrent was measured as a function of temperature and polarization direction and wavelength using an ORIEL motor-driven 77250 single grating monochromator, a globar IR source, and a lock-in amplifier. Figure 6.3 shows the normalized PV responsivity versus wavelength measured at T = 77 K for this QWIP. Two response peaks were
observed, one at $\lambda_{p1} = 8.2 \, \mu m$ with a spectral bandwidth of $\Delta \lambda / \lambda_{p1} = 11 \%$ and the other at $\lambda_{p2} = 6.0 \, \mu m$ with a spectral bandwidth $\Delta \lambda / \lambda_{p2} = 13 \%$, which are attributed to the intersubband transition from the ground bound state to the first and second continuum states above the barrier layer, respectively. Compared with the theoretical calculation, the peak $\lambda_{p1}$ has an about 6 meV blueshift at $T = 77 \, K$, while the peak $\lambda_{p2}$ has an about 18 meV redshift at $T = 77 \, K$. The blueshift of $\lambda_{p1}$ can be caused by the temperature dependence of electron effective mass, the conduction band nonparabolicity [39], the Fermi level, the conduction band offset, and the electron-electron exchange interaction [77]. Among these corrections on the subband states, the electron-electron exchange interaction is a dominant factor which could give rise to a significant blueshift as the temperature is decreased. The redshift of $\lambda_{p2}$ may be associated with defects in the InGaP barrier layers [78, 79]. The measured peak responsivity is 1,000 V/W at $\lambda_{p1} = 8.2 \, \mu m$ and 900 V/W at $\lambda_{p2} = 6.0 \, \mu m$ and $T = 77 \, K$. The detectivity $D^*_{\lambda}$ for both wavelengths is estimated to be about $3 \times 10^8 \, cm\sqrt{Hz}/W$. This low detectivity may be attributed to the sulphur-dopant loss in the well (thus lowering the oscillator absorption strength) and the formation of persistent photoconductivity in the InGaP barrier layers. The performance of this QWIP could be greatly improved by using a stable dopant impurity such as silicon [70], instead of the sulphur-dopant impurity used in the present case.

The photovoltaic behavior of this QWIP was studied in the temperature range between 77 and 30 K. The peak photovoltaic response versus inverse temperature $(100/T)$ is shown in Fig. 6.4. It is showed that the photoresponse was increased by a factor of 6 at $\lambda_{p2}$ and only a factor of 2 at $\lambda_{p1}$ as temperature decreased from 77 K to 30 K. The response at $\lambda_{p2}$ is more sensitive to the temperature change than that at $\lambda_{p1}$. This may be due to the temperature dependence of the conduction band offset $\Delta E_c$ (220 meV at 300 K). As the temperature decreases, conduction band offset $\Delta E_c$ is increased, and so does the energy band bending. As a result, the first continuum
state will be gradually immersed into the wells and converted to the confined state at temperature below 70 K, which in turn will reduce its absorption strength. Therefore, the increase in the photoresponse at $\lambda_{p1}$ will be partially offset by the reducing escape probability, whereas the photoresponse at $\lambda_{p2}$ will increase more rapidly.

6.4. Conclusions

We have demonstrated the first two-color long-wavelength GaAs/In$_{0.49}$Ga$_{0.51}$P QWIP grown by using MOCVD technique, based on the bound-to-continuum states intersubband transition and the PV mode operation. The low responsivity and detectivity observed in the MOCVD grown GaAs/InGap QWIP are attributed to the sulfur dopant loss in the quantum wells, thus leading to insufficient free carrier density in the quantum wells and low photoresponse. By using a stable dopant impurity such as silicon source during the MOCVD growth, a high performance GaAs/InGaP QWIP can be fabricated. The results reveal that the lattice-matched GaAs/In$_{0.49}$Ga$_{0.51}$P materials system grown on undoped GaAs substrate has a great potential for fabricating high performance monolithic IR focal plan arrays for IR image sensor applications.
Figure 6.1. Schematic energy band diagram (a) and transmission coefficient $|T\cdot T|$ and energy levels (b) for the GaAs/InGaP QWIP grown on GaAs by using MOCVD technique.
Figure 6.2. Typical dark current versus bias voltage for the GaAs/InGaP QWIP measured at room temperature.
Figure 6.3. Normalized PV photoresponse versus wavelength at $T = 77$ K for the GaAs/InGaP QWIP.
Figure 6.4. Peak photovoltage versus inverse temperature for the GaAs/InGaP QWIP at $\lambda_{p1} = 8.2 \mu m$ and $\lambda_{p2} = 6.0 \mu m$. 
CHAPTER 7
A NORMAL INCIDENCE TYPE-II QUANTUM WELL INFRARED PHOTODETECTOR USING AN INDIRECT BANDGAP AlAs/Al_{0.5}Ga_{0.5}As GROWN ON (110) GaAs SUBSTRATE FOR MID- AND LONG-WAVELENGTH MULTICOLOR DETECTION

7.1. Introduction

A normal incidence n-doped type-II indirect AlAs/Al_{0.5}Ga_{0.5}As quantum well infrared photodetector (QWIP) grown on (110) semi-insulating (SI) GaAs substrate with MBE technique has been developed for mid- and long-wavelength multicolor detection. The normal IR absorption for the n-doped quantum wells (QWs) was achieved in the X-band confined AlAs quantum wells. Six absorption peaks including four from X-band to Γ-band intersubband resonant transitions were observed at \( \lambda_{p1-6} = 2.2, 2.7, 3.5, 4.8, 6.5 \) and 12.5 \( \mu \)m. The resonant transport from X-band to Γ-band gives rise to high photoconductive gain and large photoresponsivity, which are highly desirable for multicolor image sensor applications.

Quantum well infrared photodetectors (QWIPs) using type-I structures have been investigated extensively in recent years [80–88]. In type-I quantum well structure, the direct bandgap material systems are usually used, hence the shape of constant energy surfaces is spherical. As a result, only the component of IR radiation with electric field perpendicular to the quantum well layers will give rise to intersubband transition. Therefore, there is no intersubband absorption for normal IR incidence in the n-doped quantum wells. In order to achieve strong absorption for normal IR radiation in the quantum wells, grating couplers [89, 90] are required to induce absorbable component from the normal IR radiation. On the other hand, the intersubband absorption for normal IR incidence from indirect bandgap semiconductors such
as SiGe/Si was observed [91, 92]. In indirect bandgap materials, conduction electrons occupy indirect valleys with ellipsoidal constant energy surfaces. The effective-mass anisotropy (mass tensor) of electrons in the ellipsoidal valleys can provide coupling between the parallel and perpendicular motions of the electrons when the principal axes of one of the ellipsoids are tilted with respect to the growth direction. As a result of the coupling, intersubband transitions at normal incidence in an indirect bandgap QWIP structure are allowed.

Since the AlAs/Al$_{0.5}$Ga$_{0.5}$As system is an indirect bandgap material, the conduction band minima for the AlAs quantum wells are located at the X-point of the Brillouin zone (BZ). The constant energy surface will also undergo change from a typical sphere at the zone center for a direct bandgap material (i.e. GaAs) to off-center ellipsoids of an indirect bandgap material (i.e. AlAs). For AlAs, there are six ellipsoids along [100] axes with the centers of the ellipsoids located at about three-fourth of the distance from the BZ center. By choosing a proper growth direction such as [110], [111], [113], or [115] direction [86, 87], due to the anisotropic band structures and the tilted growth direction with respect to principal axes of ellipsoidal valley, it is possible to realize large area normal incidence IR detection in AlAs/AlGaAs QWIPs.

7.2. Theory

The normal incidence type-II QWIP using an indirect bandgap AlAs/AlGaAs material system [86, 88] was grown on (110) SI GaAs substrate by using molecular beam epitaxy (MBE) technique. A 1.0-$\mu$m-thick n-doped GaAs buffer layer with $N_D = 2\times10^{18}$ cm$^{-3}$ was first grown on the [110] oriented SI GaAs substrate, followed by the growth of 20 periods of AlAs/Al$_{0.5}$Ga$_{0.5}$As quantum wells with a well width of 30 Å and dopant density of $2\times10^{18}$ cm$^{-3}$. The barrier layers on either side of the quantum well consist of an undoped Al$_{0.5}$Ga$_{0.5}$As (500 Å) barrier layer. Finally, a 0.3 $\mu$m thick $n^+$-GaAs cap layer with a dopant density of $2\times10^{18}$ cm$^{-3}$ was grown on top of the quantum well layers for ohmic contacts. The dopant density of $2\times10^{18}$
cm$^{-3}$ in the quantum well is chosen so that only the ground state is populated, and tradeoff between the low dark current and strong absorption strength is considered. We use the indirect bandgap AlAs for the quantum well layer and Al$_{0.5}$Ga$_{0.5}$As for the barrier layer. Since Al$_{x}$Ga$_{1-x}$As becomes an indirect bandgap material for $x > 0.45$, the conduction-band minimum shifts from the $\Gamma$-band to the X-band. Analyzing band ordering in the AlAs/Al$_{0.5}$Ga$_{0.5}$As MQW is a complicated subject in photonic device engineering [93]. We have used large enough quantum well and barrier layer thicknesses ($> 10$ monolayers) so that the QWIP under study has a type-II band structure. The conduction band offset of Al$_{0.5}$Ga$_{0.5}$As relative to AlAs is about 170 meV. Figure 7.1 shows a schematic conduction-band ($\Gamma$- and X-band) diagram for the type-II indirect AlAs/Al$_{0.5}$Ga$_{0.5}$As quantum well structure, in which electrons are confined inside the AlAs QW layer. The intersubband transition energy levels between the ground bound state ($E_0$) in the AlAs quantum well and the first excited state ($E_1$) in the well or the continuum states ($E_2 ... E_6$) above the Al$_{0.5}$Ga$_{0.5}$As barrier layers are also shown in Fig. 7.1 (a). It is noted that band splitting between the $\Gamma$-band and the X-band edge is about 50 meV in the AlGaAs layer, and the conduction band offset in the $\Gamma$-band is found to be 630 meV.

To derive the basic equations for the normal induced intersubband transitions and the corresponding indirect type-II QWIPs, we start with the Hamiltonian description of quantum mechanics for an electron [6]

$$H_o = \frac{p^2}{2m^*} + V(r) + \frac{\hbar}{4m^* c^2} \sigma \cdot (\nabla V(r) \times p),$$

(7.1)

where $m^*$, $p$, and $\sigma$ are the effective mass, momentum, and spin operators of an electron, respectively. $V(r)$ is a periodic potential function. The system under consideration consists of an assembly of electrons and the infrared radiation field. The Hamiltonian of this system, $H$, may be written as the sum of the unperturbed Hamiltonian $H_0$ and the perturbing Hamiltonian $H'_{rad}$ which represents the interaction
between the electrons and the incident infrared photon and is given by [94]

\[ H'_{rad} = -\frac{e}{m^* c} \mathbf{A} \cdot \left[ \mathbf{P} + \left( \frac{\hbar}{\lambda m^* c^2} \right) \mathbf{\sigma} \times \nabla V(\mathbf{r}) \right] , \]  

(7.2)

where \( \mathbf{A} \) is the vector potential of the IR radiation field and \( \mathbf{P} \) is the canonical momentum.

The matrix element of intersubband transition in the quantum well is given by [95, 96]

\[ M_{if} = \int \psi_{ki} H'_{rad} \psi_{kf} d\mathbf{r} = -e \left( \frac{2\pi}{V'_{cn_i \lambda \hbar \omega}} \right)^{1/2} \mathbf{e}_w \cdot \nabla_k \mathbf{E}_k \]  

where \( \psi_{ki(\text{or} f)} \) is the total wavefunction for a state in \( i \)-th (or \( f \)-th) intersubband, the parameters \( i \) and \( f \) denote the initial and the final states, \( \mathbf{e}_w \) is the unit polarization vector of the incident photon, \( \omega \) is the light frequency, \( e \) is the electronic charge, \( V' \) is the volume of the crystal, \( n_r \) is the refractive index at the wavelength of incident IR radiation, and \( \mathbf{E}_k \) is the conduction band energy of the X-valley material in the well.

It can be shown that the intersubband transition rate \( W \) may be expressed as [95, 97]

\[ W = \frac{2\pi}{\hbar} |M_{fi}|^2 \delta(E_f - E_i - \hbar \omega) \]

\[ = \frac{B_0 k^2}{\omega} \left[ \frac{\partial^2 \mathbf{E}_k}{\partial k_x \partial k_x} (\mathbf{e}_w \cdot \mathbf{x}_0) + \frac{\partial^2 \mathbf{E}_k}{\partial k_y \partial k_y} (\mathbf{e}_w \cdot \mathbf{y}_0) \right. 
\]

\[ + \left. \frac{\partial^2 \mathbf{E}_k}{\partial k_z \partial k_z} (\mathbf{e}_w \cdot \mathbf{z}_0) \right]^2 \delta(E_f - E_i - \hbar \omega) \]  

(7.4)

where \( B_0 \) is a constant equal to \( \frac{e^2 \pi^2}{c V'_{cn} \hbar^2} \); \( \mathbf{x}_0, \mathbf{y}_0, \) and \( \mathbf{z}_0 \) are the directional unit vectors. The result indicates that the nonzero intersubband transition probability at normal incidence can be obtained only when either of the crossover terms in the second partial derivatives is nonzero.

For an indirect gap type-II AlAs quantum well layer grown along [110] direction of GaAs substrate, due to the tilted anisotropic energy band with minimum point away from BZ center (see Fig. 7.1(b)), the second partial derivatives \( \frac{\partial^2 \mathbf{E}_k}{\partial k_i \partial k_i} \) (\( i = x, y \)) can be different from zero. Therefore, it is possible to excite long wavelength
intersubband transitions in the quantum well under normal incidence IR radiation. However, for a direct type-I system (i.e. GaAs) due to the isotropic spherical energy surface and the axis symmetric parabolic band \( E = E_z + \hbar^2(k_y^2 + k_z^2)/2m^* \), it always has \( \frac{\partial^2 E}{\partial k_x \partial k_i} = 0 \), (where \( i \neq z \)). The corresponding transition rate for direct type-I quantum well becomes

\[
W = \frac{B_0 k_z^2}{\omega} \left[ \frac{\partial^2 E_k}{\partial k_x \partial k_z} (e_\omega \cdot z_0) \right]^2 \delta(E_f - E_i - \hbar\omega)
\]  

(7.5)

The above equation reveals that, due to \( e_\omega \perp z_0 \), the optical transitions would become zero for type-I structures under normal incidence radiation.

### 7.3. Coupling between \( \Gamma \)- and \( X \)-bands

To analyze the intersubband transition mechanism and energy level positions in a type-II AlAs/AlGaAs QWIP, theoretical calculations of the energy states \( E_n \), \( (n = 0,1,2,...) \) for the \( X \)-band and \( \Gamma \)-band and the transmission coefficient \( |T \cdot T| \) for the QWIP were performed by using a multi-layer transfer matrix method [14]. To determine the intersubband transition levels, we use the one-band effective mass envelope function approximation (see Appendix A) and take into account the effects of band nonparabolicity and electron-electron interaction. In comparison with the more sophisticated energy band models such as two-band and three-band models, the one-band effective mass envelope function approach will give the first order approximation, thus yielding a reasonable prediction for the QWIP performance. The simulated results are summarized in Table 7.1. Each energy level listed in the Table 7.1 is referred to the center of its bandwidth. It is noted that \( E_0 \) (ground state) and \( E_1 \) (first excited state) are bound states which are confined in the AlAs \( X \)-band well, while \( E_2 \) to \( E_6 \) are all continuum states in \( X \)-band. The continuum states in the \( X \)-band can find their resonant pair levels in the \( \Gamma \)-band except \( E_2 \) which is located below the \( \Gamma \)-band minima (about 30 meV).

In a type-II indirect AlAs/AlGaAs QWIP, free carriers are confined in the AlAs quantum well formed in the \( X \)-conduction band minimum, which has a larger electron
effective mass than that in the Γ-band valley. When normal incidence radiation impinges on this QWIP, electrons in the ground-state of the X-well are excited to either the excited state $E_1$ or one of the continuum states $E_2$ to $E_6$. If the continuum state in the X-band valley is resonantly aligned with a state in the Γ-band valley, the photon-generated electrons in the X-band will undergo resonant transport to the resonant state in the Γ-band provided that the Γ-band barrier layer (in the present case, AlAs layer) is so thin that it is transparent to the conduction electrons [99, 100]. This resonant transport from X-band to Γ-band is expected to be a coherent resonance which can greatly enhance the transmission if the electron lifetime $\tau_L^\Gamma$ in these continuum states is much shorter than the X-band to Γ-band scattering time constant $\tau_S$. The $\tau_L^\Gamma$ can be estimated from the uncertainty principle, $\tau_L^\Gamma = \frac{\hbar}{\Delta E_{FWHM}} \sim 10$ fs (where $\Delta E_{FWHM}$ is the spectral full width at half maximum), while $\tau_S \sim 1$ ps [19], hence $\tau_L^\Gamma \ll \tau_S$. The peak transmission at resonance is expected to be increased by the ratio of $\tau_S/\tau_L^\Gamma \sim 100$. In addition, due to the effective mass difference between the X-band and the Γ-band, electron velocity and mobility in the Γ-valley will be much higher than the value in the X-band valley. Since the photocurrent is proportional to the electron velocity and mobility (i.e., $I_{ph} = A_d v_d G \tau_R$, where $A_d$ is the effective area of the detector, $v_d$ is the drift velocity, $G$ is the photogeneration rate, $1/\tau_R$ is the recombination rate of electrons in the Γ-band), a large increase in the photocurrent is expected when photon-generated electron resonant transport from the X-band to Γ-band takes place under certain bias conditions as illustrated in Fig. 7.2. It is known that photoconductive gain $g = \tau_L/\tau_T$, where $\tau_T$ is transit time (= $\frac{l}{F \mu}$, $l$ superlattice thickness, $\mu$ electron mobility, and $F$ electric field). In the coherent resonance and certain bias condition, the gain $g$ will be significantly enlarged as well.

7.4. Experiments

A BOMEN interferometer was used to measure the infrared absorbance of the AlAs/AlGaAs QWIP sample. In order to eliminate substrate absorption, we per-
formed absorbance measurements with and without the quantum well layers. The absorbance data were taken using normal incidence at 77 K and room temperature. The absorption coefficients deduced from the absorbance data are shown in Fig. 7.3. Two broad absorption peaks at wavelengths $\lambda_p = 6.8 \mu m$ and $14 \mu m$ were detected, while four additional narrow absorption peaks at $\lambda_p = 2.3 \mu m$, $2.7 \mu m$, $3.5 \mu m$, and $4.8 \mu m$ at NIR were also observed. The measured absorption peak wavelengths are in excellent agreement with the theoretical prediction. All the absorption coefficients measured at 77 K were found to be about a factor of 1.2 higher than the room temperature values. From our theoretical analysis, the $14 \mu m$ peak with an absorption coefficient of about $2000 \text{ cm}^{-1}$ is attributed to the transition between the ground state $E_0$ and the first excited state $E_1$ in quantum well, while the $6.8 \mu m$ peak with absorption coefficient of about $1600 \text{ cm}^{-1}$ is due to transition between the ground state $E_0$ and the continuum state $E_2$. The absorption peaks at $2.3 \mu m$, $2.7 \mu m$, $3.5 \mu m$, and $4.8 \mu m$ are attributed to the transitions between the ground state $E_0$ and other high order continuum states listed in Table 7.1. It is interesting to note that the high order intersubband transitions have relatively larger absorption coefficient of about $4000 \text{ cm}^{-1}$, which is quit different from the intersubband transition in type-I QWIPs. However, the absorption at $6.8 \mu m$, which is also due to the transition between bound state and continuum state, has a small absorption coefficient compared to the other high order continuum transitions. This indicates that the $6.8 \mu m$ absorption peak has a different absorption and conduction mechanism, which we shall discuss it later.

To facilitate the normal incidence IR illumination, an array of $210 \times 210 \mu m^2$ mesas were chemically etched down to $n^+\text{-GaAs}$ buffer contact layer on the GaAs substrate. Finally, AuGe/Ni/Au ohmic contacts were formed on the QWIP structures, leaving a central sensing area of $190 \times 190 \mu m^2$ for normal incidence illumination on top contact of the QWIP. Device characterization was performed in a liquid-helium cryogenic dewar. A HP4145 semiconductor parameter analyzer was used to measure
the dark current versus bias voltage. Figure 7.4 shows the measured dark current as a function of the bias voltage for temperatures between 68 and 98 K. Substantial reduction of device dark current was achieved in the present type-II structure. The photocurrent was measured using a CVI Laser Digikrom 240 monochromator and an Oriel ceramic element infrared source. A pyroelectric detector was used to calibrate the radiation intensity from the source. The measured data for the QWIP are tabulated in Table 7.2, which showed six absorption peaks. The peaks for $\lambda_{p1,2}$ only exhibited the photoconductive (PC) detection mode, while the peaks for $\lambda_{p3,6}$ operated in both the PC mode and photovoltaic (PV) mode.

Figure 7.5 shows the QWIP’s photoresponse and absorption coefficient for wavelengths from 9 to 18 μm. The peak photoresponse was observed at $\lambda_{p1} = 12.5$ μm with a cutoff wavelength at 14.5 μm and a peak responsivity of $R_A = 24$ mA/W at $T = 77$ K and $V_b = -2$ V. A broader spectral bandwidth of $\Delta \lambda / \lambda_{p1} = 30\%$ was obtained for this QWIP, which is larger than the type-I QWIP [58]. The property of a broader spectral bandwidth within X-band intersubband transition was also found in [113] GaAs substrate growth direction [87, 98]. Detectivity for this peak wavelength $\lambda_{p1} = 12.5$ μm was found to be about $1.1 \times 10^9$ cm$^{-1}$Hz/W under the above specified condition. A relative small absorption peak at $\lambda_{p2} = 6.5$ μm was detected, which is attributed to the transition between the ground state $E_0$ and the first continuum state $E_2$. The peak responsivity for $\lambda_{p2}$ was found to be about $R_A = 5$ mA/W at $T = 77$ K and $V_b = -2$ V, which was not shown in the figure. About $8 \sim 11$ meV blueshifts were found at these two peak wavelengths.

Figure 7.6 shows the normalized photovoltaic (PV) spectral response bands at the peak wavelengths of $\lambda_{p4} = 3.5$ μm and $\lambda_{p6} = 2.2$ μm. The two spectral response bands cover wavelengths from 2.2 μm to 6.5 μm for peak wavelength at $\lambda_{p4} = 3.5$ μm and from 2.0 μm to 3.25 μm for peak wavelength at $\lambda_{p6} = 2.2$ μm. The spectral band for $\lambda_{p6}$ has an additional peak at $\lambda_{p5} \sim 2.7$ μm, while the spectral band for $\lambda_{p4}$ also
has a large tail which results from another peak contribution at about $\lambda_{p3} \sim 4.8 \, \mu m$. The positions for all four peak wavelengths $\lambda_{p3-6}$ are in excellent agreement with the values deduced from the FTIR measurements and theoretical calculations. The main peak responses occurred at $\lambda_{p4} = 3.5 \, \mu m$ and $\lambda_{p6} = 2.2 \, \mu m$ with responsivities of $R_A = 29 \, mA/W$ and $32 \, mA/W$, respectively, at $V_b = 0 \, V$ and $T = 77 \, K$. The responsivities of two main peaks have a different voltage dependence. The peak for $\lambda_{p4}$ increases rapidly for $V_b > -0.5 \, V$, and it reaches a saturation responsivity value of $18.3 \, A/W$ at $V_b \geq -3 \, V$ as shown in Fig. 7.7. On the other hand, the responsivity for $\lambda_{p6}$ remains nearly constant for $V_b \leq -2 \, V$, and then exponentially increases to $R = 110 \, A/W$ at $V_b \sim -6 \, V$, as shown in Fig. 7.8. Extremely large photoconductivity gains of 630 and 3,200 for $\lambda_{p4}$ and $\lambda_{p6}$ (as compared to the value at $V_b = 0 \, V$) were obtained at $V_b = -3 \, V$ and -6 V, respectively. The larger responses at $\lambda_{p4}$ and $\lambda_{p6}$ wavelengths are due to a better alignment of these resonant levels, while the relatively lower responses for the $\lambda_{p3}$ and $\lambda_{p5}$ wavelengths are ascribed to a slightly misalignment in the resonant levels, which results from the $\Gamma$-$X$ coupling strength difference [101]. However, no photoconductivity gain is expected to be observed at $\lambda_{p1}$ and $\lambda_{p2}$ peak wavelengths due to the absence of the resonant transition from the X-band to the $\Gamma$-band in the electronic conduction.

The PV mode operation at peak wavelengths of $\lambda_{p3-6}$ in the type-II AlAs/AlGaAs QWIP is resulted from the macroscopic polarization field (i.e. Hartree potential) caused by the energy band bending effect and spatial separation of electrons and holes [45, 58, 102, 103]. However, the PV operation was not observed in the wavelengths of $\lambda_{p1-2}$. This is probably due to the novel resonant transport feature which enhances the photogenerated electron conduction.
7.5. Conclusions

In conclusion, we have demonstrated a normal incidence type-II QWIP using an indirect X-band AlAs/Al$_{0.5}$Ga$_{0.5}$As system grown on (110) GaAs substrate with multicolumn responses for 2 ~ 18 μm wavelength detection. The desirable normal incidence radiation is allowed due to the tilted and anisotropic energy band structure of AlAs/AlGaAs grown on (110) GaAs substrate. The detector was found to have six peak wavelength responses at $\lambda_{p1-6} = 12.5, 6.5, 4.8, 3.5, 2.7$ and 2.2 μm. The spectral responses for wavelengths at $\lambda_{p3-6} = 4.8, 3.5, 2.7$, and 2.2 μm are ascribed to the novel resonant interaction between the X-band and Γ-band that yields a large photoconductive gain in electron conduction. The spectral response at wavelength of 12.5 μm has a broader bandwidth ($\Delta \lambda/\lambda_{p1} = 30 \%$), covering wavelength ranging from 9 to 18 μm. The capabilities of normal incidence, large spectral sensing range, ultra high photoconductive gain, multicolumn detection, and ultra low noise characteristics make the type-II AlAs/AlGaAs QWIPs highly desirable for many infrared applications. Further studies of the interaction effects between the X- and Γ-bands, transition coupling, bandgap engineering, and hot electron transport mechanisms in the type II indirect III-V multiple quantum well structures may lead to the development of novel quantum well infrared detectors, lasers, and modulators.
Table 7.1. The simulated intersubband transition energy levels in the X-band and Γ-band for the type-II AlAs/AlGaAs QWIP.

<table>
<thead>
<tr>
<th></th>
<th>E₀</th>
<th>E₁</th>
<th>E₂</th>
<th>E₃</th>
<th>E₄</th>
<th>E₅</th>
<th>E₆</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-band</td>
<td>20</td>
<td>110</td>
<td>189</td>
<td>270</td>
<td>365</td>
<td>475</td>
<td>600</td>
</tr>
<tr>
<td>Γ-band</td>
<td></td>
<td></td>
<td></td>
<td>265</td>
<td>370</td>
<td>460</td>
<td>595</td>
</tr>
</tbody>
</table>

Notes: The energy levels, E₃, E₄, E₅, and E₆ in the Γ-band and X-band formed the resonant levels for the photoexcited electrons in this QWIP. The parameters used in calculation of X-band and Γ-band, respectively, are m* = 0.78 m₀, 0.15 m₀ for AlAs and 0.82 m₀, 0.11 m₀ for Al₀.₅Ga₀.₅As. (All the energy levels shown are measured from the AlAs quantum well X-conduction band edge in unit of meV.)
Table 7.2. The measured peak wavelengths, responsivities, and detectivities for the type-II AlAs/AlGaAs QWIP at $T = 77$ K.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_{p1}$</th>
<th>$\lambda_{p2}$</th>
<th>$\lambda_{p3}$</th>
<th>$\lambda_{p4}$</th>
<th>$\lambda_{p5}$</th>
<th>$\lambda_{p6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak ($\mu$m)</td>
<td>12.5</td>
<td>6.5</td>
<td>4.8</td>
<td>3.5</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td>$R_A$ (A/W) (PV)</td>
<td></td>
<td></td>
<td></td>
<td>0.029</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>$R_A$ (A/W) (PC)</td>
<td>0.024</td>
<td>0.005</td>
<td></td>
<td>18.3</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>$V_2$</td>
<td>2 V</td>
<td>2 V</td>
<td></td>
<td>3 V</td>
<td></td>
<td>6 V</td>
</tr>
<tr>
<td>$D_A^*$ (cm$\sqrt{Hz}$/W)</td>
<td>$1.1 \times 10^9$</td>
<td>$3.0 \times 10^{11}$</td>
<td>$1.1 \times 10^{12}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 7.1. (a) The conduction band diagram for the type-II AlAs/Al$_{0.5}$Ga$_{0.5}$As QWIP. The solid line is for the X-band and the dashed line denotes the $\Gamma$-band. (b) The six ellipsoids of X-band minima along the (100) axes with center of the ellipsoids located at about three-fourth of the distance from BZ center for AlAs. The preferred [110] growth direction is indicated by the arrow.
Figure 7.1. Continued.
Figure 7.2. Schematic diagram of the conduction band minima for L-, Γ-, and X-valleys. Γ-X coupling transport is illustrated by the dot-dashed arrow.
Figure 7.3. Absorption coefficients versus wavelength measured by BOMEN interferometer at normal incidence for the AlAs/AlGaAs QWIP at $T = 77$ K and room temperature.
Figure 7.4. Dark currents versus negative bias voltage for the AlAs/AlGaAs QWIP measured at $T = 68, 77, 98$ K, respectively.
Figure 7.5. Spectral responsivity and absorption coefficient versus wavelength for $\lambda_{p1} = 12.5$ $\mu$m transition at normal incidence, $V_b = -2$ V and $T = 77$ K for the AlAs/AlGaAs QWIP.
Figure 7.6. Normalized spectral responsivities versus wavelength for $\lambda_{p4} = 3.5 \, \mu m$ and $\lambda_{p6} = 2.2 \, \mu m$ transitions for the AlAs/AlGaAs QWIP measured at $V_b = 0 \, V$ and $T = 77 \, K$. 
Figure 7.7. Responsivity versus negative bias voltage at the peak wavelength $\lambda_{p4} = 3.5 \, \mu m$ and $T = 77 \, K$ for the AlAs/AlGaAs QWIP.
Figure 7.8. Responsivity versus negative bias voltage at the peak wavelength $\lambda_{p6} = 2.2 \, \mu m$ and $T = 77 \, K$ for the AlAs/AlGaAs QWIP.
8.1. Introduction

Quantum well infrared photodetectors (QWIPs) using n-type GaAs/AlGaAs and InGaAs/InAlAs material systems for the 3 - 5 \( \mu \text{m} \) mid-wavelength infrared (MWIR) and 8 - 14 \( \mu \text{m} \) long-wavelength infrared (LWIR) atmospheric transmission windows have been extensively studied in recent years [56]. With low electron effective mass and high electron mobility, the n-type GaAs and InGaAs QWIPs offer excellent IR detection properties. However, quantum mechanical selection rule for the intersubband transition requires that the radiation electric field has a component perpendicular to the quantum well plane in order to induce intersubband absorption in the quantum wells. As a result, for n-type QWIPs, it is necessary to use planar metal or dielectric grating structures for coupling the normal incident IR radiation into absorbable angles [48, 89, 90].

P-type QWIPs using valence intersubband transitions have been demonstrated in the lattice-matched GaAs/AlGaAs and InGaAs/InAlAs material systems [104, 105, 106, 107]. Due to band mixing between the light-hole and heavy-hole states, the normal incident illumination is allowed for the intersubband transition in p-type QWIPs. In general, the intersubband transitions under normal incident radiation in p-type quantum wells are induced by the linear combination of P-like valence-band Bloch states that provides a nonzero coupling between these components and the normal radiation field. The strong mixing between the light- and heavy-hole states for \( k \neq 0 \) greatly enhances the normal incidence intersubband absorption. However, in the unstrained lattice-matched quantum well systems, these intersubband transitions
occur between the heavy-hole ground state and the upper heavy-hole excited states. Due to large heavy-hole effective mass, weak absorption and low responsivity are expected in the unstrained p-QWIPs.

Strain effects induced by lattice-mismatch can modify the energy bandgap of quantum well/superlattice, split the degeneracy of the heavy- and light-hole bands at the center of Brillouin Zone (BZ) as shown schematically in Fig. 8.1, and modify carrier transport properties [108]. Matthews and Blakeslee [109] reported that a high quality of coherently strained-layers can be grown if the individual layer thickness of the system is within its critical thickness. Osbourn [9, 110] demonstrated that coherently strained-layer superlattices (SLS) can be used for a wide variety of novel optoelectronic devices such as lasers, modulators, enhanced-mobility field effect transistors, light-emitting diodes, and photodetectors.

8.2. Theory

When a biaxial strain is applied between two thin superlattice layers, the pseudomorphic or coherent heterointerfaces can be obtained if the individual layer thickness is within the critical thickness. As a result, the misfit due to the lattice constant mismatch is totally accommodated by the elastic strain. The biaxial strain can be either compressive or tensile depending on the lattice constants and layer growth direction. Based on the force balance model [109], the equilibrium critical layer thickness $h_c$ for an epilayer with lattice constant $a$ grown on a substrate with a lattice constant $a_s$ is given by

$$h_c = \left( \frac{a}{\sqrt{2} \delta_o} \right) \frac{1 - \nu \cos^2 \Theta}{8\pi(1 + \nu) \cos \alpha} \left[ 1 + \ln(h\sqrt{2}/a) \right]$$  \hspace{1cm} (8.1)

where $h$ is the epilayer thickness, $\Theta$ is the angle between dislocation line and Burgers' vector, $\alpha$ is the angle between slip direction and the layer plane direction, $\delta_o$ is the lattice-mismatch or in-plane strain, $\delta_o = (a_s - a)/a$, ($\delta_o > 0$ for tensile strain, $\delta_o < 0$ for compressive strain), and $\nu$ is the Poisson ratio, $\nu = -C_{12}/C_{11}$. $C_{ij}$ are the elastic constants which can be found in reference [111].
For a coherent strained multiple layer QWIP structure, the multilayers can also be grown on a substrate having a lattice constant \( a_s \) with misfit-free quality if \( a_s = a_{\parallel} \), where \( a_{\parallel} \) is the equilibrium in-plane lattice constant for the multi-layers. It can be calculated by [109]

\[
a_{\parallel} = \frac{a_1 \xi_1 L_1 + a_2 \xi_2 L_2}{L_1 \xi_1 + L_2 \xi_2},
\]

(8.2)

where \( a_{1,2} \) and \( L_{1,2} \) are the individual layer lattice constant and thickness, respectively. \( \xi \) is the shear modulus given by \( \xi = (C_{11} + C_{12} - 2C_{12}^2/C_{11}) \). In the case \( a_{\parallel} \neq a_s \), the coherently strained-layer superlattice structure is no longer in equilibrium with the substrate. For instance, if the lattice constant of the barrier layers is equal to that of substrate, then the strain will be entirely accommodated in the well layers with no strain in the barrier layers. However, Hull et al. [112] showed that, even though \( a_{\parallel} \neq a_s \), if the individual layer thickness in the superlattice is less than its critical thickness, the loss of coherence only occurs at the interface between whole superlattice and substrate, and whole superlattice still remains coherent itself. If the coherently strained-layer structure of a QWIP is grown along [100] direction, the components of the strain tensor \( [e] \) for layers are reduced to

\[
\begin{align*}
e_{xx} &= e_{yy} = e_{\parallel} = \frac{a_s - a_{\parallel}}{a_{\parallel}}; \\
e_{zz} &= -e_{\parallel} \left( \frac{2C_{12}}{C_{11}} \right); \\
e_{xy} &= e_{yz} = e_{zx} = 0.
\end{align*}
\]

(8.3) (8.4) (8.5)

In order to fully describe the optical and electronic properties (such as energy bandgap, subband energy level splitting, intersubband transition etc.,) for a coherently strained-layer structure, the multiband effective-mass k.p model based on the perturbation approximation should be used. In the k.p model, the interactions of S-P type coupling among conduction (C), heavy-hole (HH), light-hole (LH), and spin-orbit (SO) states combined with spinorlike coupling are taken into consideration to derive the band structures, thus, resulting in \( 8 \times 8 \) k.p Hamiltonian and momentum
matrix elements. Under the perturbation approximation, a set of wave functions of $S_{1/2}$: $(|1/2, \pm 1/2 >)$, $P_{3/2}$: $(|3/2, \pm 3/2 >; |3/2, \pm 1/2 >)$, and $P_{1/2}$: $(|1/2, \pm 1/2 >)$ are used as the unperturbed and unstrained basis in the $|J, m_J >$ representation [113]. $m_J = \pm 1/2$ represent light-particle states (either for electron or for LH), while $m_J = \pm 3/2$ denote heavy-particle states (for HH). When a larger bandgap exists such as in InGaAs and GaAs layers compared with the elements of the k.p matrix between the conduction band and valence band states, a reduced $6 \times 6$ k.p Hamiltonian can be roughly used to depict the P-like properties of the coherently strained-layers by considering the S-like conduction band states as a perturbation. The wave functions of the coherently strained-layer superlattice at the zone center (i.e. $k = 0$) are given by [114],

$$|3/2, \pm 3/2 > \text{ HH states} \quad (8.6)$$
$$\gamma|3/2, \pm 1/2 > + \beta|1/2, \pm 1/2 > \text{ LH states} \quad (8.7)$$
$$-\beta|3/2, \pm 1/2 > + \gamma|1/2, \pm 1/2 > \text{ SO states} \quad (8.8)$$

where $\gamma$ and $\beta$ are constants depending on the strain parameters. It is seen that the heavy-hole states $|3/2, \pm 3/2 >$ are still decoupled with other valence states even under the biaxial strain at $k = 0$, while light-hole states and spin-orbit split-off states are coupled at $k = 0$. However, HH, LH, and SO states are variedly mixed [115, 116] in the coherently strained-layer superlattice if $k \neq 0$. This kind of mixtures (between the states with different $m_J$'s) is due to boundary conditions across the interface of the quantum well layers. From the k.p matrix, the interaction between the different $m_J$'s states is proportional to the transverse components of the wave vector (i.e. $k_{x,y}$), so that HH-states are decoupled when $k_{x,y} = 0$. Note that $k_{x,y}$ are conserved across the interfaces since interface potential depends only on $z$, the quantum well growth direction. The band mixing can be significant if the $\Gamma$-bandgap is small (e.g., GaAs and InGaAs) and if LH- and SO-bands involved in the transition have a large $k_z$ [115].

From the elasticity theory [108], the biaxial strain can be divided into two in-
dependent components, one is isotropic or hydrostatic component and the other is anisotropic or shear uniaxial component. The strain-induced energy shifts, \( \Delta E_H \) due to the hydrostatic component and \( \Delta E_U \) due to the shear uniaxial component, can be expressed, respectively, by [117]

\[
\Delta E_H = 2V_{cd} \frac{C_{11} - C_{12}\delta_o}{C_{11}} \tag{8.9}
\]

\[
\Delta E_U = V_{sd} \frac{C_{11} + 2C_{12}\delta_o}{C_{11}} \tag{8.10}
\]

where \( V_{cd} \) and \( V_{sd} \) are the conduction-band deformation potential and shear deformation potential, respectively.

The energy bandgaps due to the strain for the heavy-hole, light-hole, and spin-orbit states at \( \mathbf{k} = 0 \) are given by [117]

\[
E_{HH} = E_{go} + \Delta E_H - \Delta E_U \tag{8.11}
\]

\[
E_{ LH} = E_{go} + \Delta E_H + \Delta E_U - \frac{(\Delta E_U)^2}{2\Delta_o} + \cdots \tag{8.12}
\]

\[
E_{SO} = E_{go} + \Delta_o + \frac{(\Delta E_U)^2}{2\Delta_o} + \cdots \tag{8.13}
\]

where \( E_{go} \) is the unstrained bandgap and \( \Delta_o \) is the spin-orbit splitting energy. From the above equations, it can be shown that both the heavy-hole and light-hole states can be shifted as a result of the biaxial strain and spin-orbit splitting energy.

The calculation of both intersubband and interband transitions in a p-type strained-layer QWIP requires the use of 6×6 Hamiltonian which includes the above \( \mathbf{k.p} \) Hamiltonian [114] and the strain Hamiltonian [108]. The strain and spin-orbit coupling terms do not lift the spin degeneracy, and hence the 6×6 Hamiltonian matrix can be factorized into two 3×3 irreducible matrices. In order to simplify the problem without lost correct prediction, we assume Fermi distribution function is equal to one for the confined ground state and zero for the excited states in equilibrium. The absorption coefficient for the intersubband (or interband) transition between the initial
ground state $i$ and the final continuum states $f$ is given by [118]
\[
\alpha_i(\omega) = \sum_f \frac{4\pi^2 e^2}{n_r c m_0^2 \omega} \int_{BZ} \frac{2dk}{(2\pi)^3} \left[ (f_i - f_f)|\hat{\epsilon} \cdot \mathbf{P}_{i,f}|^2 \frac{\Gamma/2\pi}{[\Delta_{i,f}(k) - \hbar \omega]^2 + \Gamma^2/4} \right]
\]

(8.14)

where $n_r$ is the refractive index in the quantum well, $m_0$ is the free electron mass, $\Delta_{i,f}$ is the energy difference between the initial state $i$ (with energy $E_i(k)$) and the final state $f$ (with energy $E_f(k)$), $\hat{\epsilon}$ and $\omega$ are the unit polarization vector and the frequency of the incident IR radiation, $f_i$ (or $f_f$) is the Fermi distribution function of initial (or final) state, $\Gamma$ is the full width of level broadening ($\sim \hbar/\tau_f$, $\tau_f$ lifetime between states $i$ and $f$). $|\hat{\epsilon} \cdot \mathbf{P}_{i,f}|$ is the optical transition elements between the quantum well valence ground subband states $i$ and the continuum subband states $f$ in HH-, LH-, and SO-bands, and can be derived from two $3 \times 3$ k.p matrix elements (see Appendix B). The optical transition elements show the selection rule of the intersubband transition for the p-type coherently strained-layer quantum well. For the same type intersubband transitions such as HH$\leftrightarrow$HH, LH$\leftrightarrow$LH, and SO$\leftrightarrow$SO, the oscillator strength is proportional to either $k_\perp$ (or $k_z$) or $k_\parallel$ (or $k_{x,y}$). For the mixing type interband transitions such as HH$\leftrightarrow$LH, HH$\leftrightarrow$SO, and LH$\leftrightarrow$SO, each polarization of the normal incident light can contribute to the intersubband absorption.

8.3. A Tensile Strained-layer InGaAs/InAlAs QWIP

A p-type tensile strained-layer (PTSL) In$_{0.3}$Ga$_{0.7}$As/In$_{0.52}$Al$_{0.48}$As quantum well infrared photodetector (QWIP) grown on semi-insulating (100) InP substrate with MBE technique for 8-14 $\mu$m detection has been developed. This PTSL-QWIP shows background limited performance (BLIP) for $T \leq 100$ K, which is the highest BLIP temperature ever reported for the QWIP family [119].
8.3.1. Inversion between Heavy- and Light-hole States

Due to the lattice mismatch between the InP substrate and the In$_{0.3}$Ga$_{0.7}$As quantum well, a biaxial tensile strain is created in the quantum well while no strain exists in the barrier layer [120, 121]. The tensile strain in the wells can push the light-hole levels upward and pull the heavy-hole levels downward. As a result, the ground heavy-hole and light-hole states are inverted for a certain strain and quantum well thickness, and the light-hole state becomes the ground state in the quantum well. Thus for the PTSL-QWIP, the intersubband transition is from the populated light-hole ground state to the heavy-hole continuum states. Since the light-hole has a small effective mass, the optical absorption and photoresponsivity in the PTSL-QWIP can be greatly enhanced by using this new approach. In fact, the calculated absorption coefficient by Xie et al. [120] for the In$_{0.3}$Ga$_{0.7}$As/In$_{0.52}$Al$_{0.48}$As system with a 60 Å well width was found to be 8,500 cm$^{-1}$ at $\lambda_p = 12 \mu$m.

8.3.2. Experiments

The normal incidence p-type tensile strained-layer In$_{0.3}$Ga$_{0.7}$As/In$_{0.52}$Al$_{0.48}$As QWIP uses the intersubband transition scheme between the confined ground light-hole state to the continuum heavy hole states. Figure 8.2 shows the energy band diagram for the PTSL-QWIP. The band bending may be attributed to the dopant migration effect occurred during the layer growth. The PTSL-QWIP structure was grown on a (100) semi-insulating (SI) InP substrate by using MBE technique. The PTSL-QWIP structure consists of 20 periods of 4-nm Be-doped In$_{0.3}$Ga$_{0.7}$As quantum well with a dopant density of $1 \times 10^{18}$ cm$^{-3}$ separated by 45-nm In$_{0.52}$Al$_{0.48}$As undoped barrier layer. A 0.3-μm cap layer and a 1-μm buffer layer of Be-doped In$_{0.53}$Ga$_{0.47}$As with a dopant density of $2 \times 10^{18}$ cm$^{-3}$ were grown for the top and bottom ohmic contacts. The contact and barrier layers are lattice-matched to the InP substrate, and the quantum well layer is in biaxial tension with a lattice mismatch of approximately 1.5%. In order to measure the spectral responsivity and dark current of this
PTSL-QWIP, a 200 × 200 μm² mesa structure was created by using the chemical etching process. The Au/Zn alloy was thermally evaporated onto the QWIP mesas with a film thickness of 1500 Å, followed by annealing at 480 °C for 3 minutes to obtain stable and low contact resistance.

Figure 8.3 shows the measured dark current density and 300-K background photocurrent density for the PTSL-QWIP. The device shows asymmetric dark current characteristic under positive and negative bias, which is attributed to the band bending due to dopant migration effect as shown in Fig. 8.2. The dark current density was found to be equal to 7×10⁻⁸ A/cm² at V_b = 2 V and T = 77 K. In fact, this PTSL-QWIP is under background limited performance (BLIP) with field of view (FOV) 90°C for V_b ≤ 3 V and T ≤ 100 K, which is believed to be the highest BLIP temperature ever observed in a QWIP. The ultra low dark current density observed in the PTSL-QWIP can be attributed to the following factors, (1) the dark current is dominated by the thermionic emission from the ground light-hole state and transports through the heavy-hole continuum states above the barrier. The thermionic emission current is drastically reduced due to the increase of the effective barrier height by the strain in the quantum well, (2) since the bandwidth of the heavy-hole continuum states is very narrow (∼ 10 meV compared to the unstrained p-type QWIP of about 25 meV), a reduction of dark current by about ten times is expected, (3) due to large heavy-hole effective mass and short heavy-hole lifetime in the continuum states (i.e., lower photoconductive gain) the dark current can be further reduced, and (4) lower thermally generated hole density also contributes to a lower dark current.

The responsivity of the QWIP under normal incidence illumination was measured as a function of temperature, bias voltage, and wavelength using a globar and automatic PC-controlled single-grating monochromater system. The measured photocurrents versus wavelength for both positive and negative biases are shown in Fig. 8.4 (a) and (b), respectively. A peak response wavelength was found to be at λ_p = 8.1
µm, which is attributed to the intersubband transition between the confined ground light-hole state $E_{LH1}$ to the continuum heavy-hole band states $E_{HH3}$ as illustrated in Fig. 8.2. The cutoff wavelength for this QWIP was found to be 8.8 µm with a spectral bandwidth of $\Delta \lambda/\lambda_p = 12 \%$. Since two other heavy-hole bound excited states are confined inside the quantum wells with very low tunneling probability off the thicker barrier layer, no photoresponse from these two heavy-hole states was detected. The responsivities for the PTSL-QWIP were calibrated by using a standard pyroelectric detector and lock-in amplifier technique. Responsivities of 34 mA/W at $V_b = 4$ V and 51 mA/W at $V_b = -4$ V were obtained for this PTSL-QWIP. The maximum BLIP detectivity $D^*_{BLIP}$ at $\lambda_p = 8.1$ µm was found to be $5.9 \times 10^{10}$ cm-$\sqrt{Hz}$/W (with a responsivity $R_A = 18$ mA/W) at $V_b = 2$ V, FOV = 90° and $T = 77$ K. The quantum efficiency for the PTSL-QWIP was estimated to be 18% from the responsivity measurement with a photoconductive gain $g = 0.015$.

When Johnson noise and readout circuit noise are ignored, %BLIP for positive and negative bias are evaluated by using

$$\%BLIP \approx \frac{i_{nb}}{(i_{nb}^2 + i_{nd}^2)^{1/2}}$$

where $i_{nb,nd}$ are the 300 K background photocurrent noise and dark current noise, respectively. The insets in Fig. 8.4 show the calculated %BLIP results for the positive and negative biases. A nearly full BLIP detection was achieved at bias voltage between -2 V and 5 V. As a result of the full BLIP detection in our PTSL-QWIP, the noise equivalent temperature difference (NE∆T) in the focal plane array imaging applications is expected to be significantly improved.

8.3.3. Conclusions

We have demonstrated a new normal incidence p-type tensile strained-layer In-GaAs/InAlAs QWIP with BLIP for $V_b \leq 3$ V and $T \leq 100$ K. The BLIP detectivity for the PTSL-QWIP was greatly enhanced by the biaxial tensile strain introduced in the wells leading to the inversion of heavy- and light-hole subbands in the well.
By further optimizing the quantum well dopant density, biaxial strain strength, and structure parameters, high performance PTSL-QWIPs can be fabricated for large-area infrared focal plane array image sensor system under BLIP for $T \leq 100$ K.

8.4. A Compressive Strained-layer InGaAs/GaAs QWIP

A normal incidence p-type compressive strained-layer (PCSL) In$_{0.4}$Ga$_{0.6}$As/GaAs quantum well infrared photodetector (QWIP) grown on (100) semi-insulating GaAs substrate by MBE technique for 3-5 $\mu$m MWIR and 8-14 $\mu$m LWIR two-color detection has been demonstrated for the first time. This PCSL-QWIP shows a broadband double-peak response at MWIR and LWIR detection bands by utilizing the resonant transport coupling mechanism between the heavy-hole type-I states and the light-hole type-II states. By using the compressive strain in the InGaAs quantum well [122], normal incidence absorption was greatly enhanced by reducing the heavy-hole effective mass (by a factor of 3) and increasing the density of states off zone center. Maximum responsivities of 93 mA/W and 30 mA/W were obtained at peak wavelengths of $\lambda_{p1} = 8.9$ $\mu$m and $\lambda_{p3} = 5.5$ $\mu$m, respectively, with $V_b = 1.6$ V and $T = 70$ K. Detectivity at $\lambda_{p1} = 8.9$ $\mu$m was found to be $4.0 \times 10^9$ cm-$\sqrt{Hz}/W$ at $V_b \leq 0.3$ V and $T = 70$ K.

8.4.1. Interaction between Type-I and Type-II QW States

In general, strain can strongly affect the energy band structure and induce splitting between the heavy-hole and light-hole states in the valence band zone-center, which is degenerated in the unstrained case. In the In$_{0.4}$Ga$_{0.6}$As/GaAs QWIPs, a biaxial compressive strain is introduced in the InGaAs quantum well layers while no strain is present in the GaAs barrier layers. The strain pushes the heavy-hole states upward and pulls the light-hole states downward in the InGaAs well region. The light- and heavy-hole bands are split in the InGaAs well region and degenerated in the GaAs barrier region at the Brillouin zone (BZ) center (i.e. $k = 0$).

The p-type compressive strained-layer In$_{0.4}$Ga$_{0.6}$As/GaAs PCSL-QWIP was grown
on a SI GaAs substrate by using MBE technique. This PCSL-QWIP structure consists of 20 periods of 4-nm Be-doped In$_{0.4}$Ga$_{0.6}$As quantum well with a dopant density of $4 \times 10^{18}$ cm$^{-3}$ separated by a 35-nm GaAs undoped barrier layer. A 0.3-µm cap layer and a 0.7-µm buffer layer of Be-doped GaAs with a dopant density of $5 \times 10^{18}$ cm$^{-3}$ were grown for the top and bottom ohmic contacts. The contact and barrier layers are lattice-matched to the SI GaAs substrate, and the In$_{0.4}$Ga$_{0.6}$As quantum well layers are under biaxial compression with a lattice mismatch of approximately 2.8%.

The ground subband energy levels confined in the quantum wells are the highly populated heavy-hole states $E_{HH1}$. The mobility of the heavy-hole is enhanced by the compressive strain created in the InGaAs quantum well layers due to the reduction of the heavy-hole effective mass [123] (i.e., by a factor 3). In addition, due to the compressive strain in the quantum well, the density of states in the well will decrease, and hence many more free holes have to reside at higher energy states, which implies that the effective Fermi level is elevated by the compressive strain effect compared to the unstrained case. The elevation of the effective Fermi level will result in the increase of the number of the off-BZ-center free holes (i.e., $k \neq 0$) with lighter effective mass, and hence a larger intersubband absorption under normal IR incidence is expected.

In this InGaAs/GaAs strained-layer QWIP, heavy-holes are in type-I band alignment configuration, while light-holes are in type-II band alignment configuration. In addition, a binary GaAs barrier layer is employed so that a superior current transport is expected to that of a ternary barrier layer. It should be noted that unlike other types of QWIPs, the heavily doped contact layers of this PCSL-QWIP are made on large-bandgap GaAs. A large tunneling current from the triangle barrier potential near the ohmic contact region may be the dominant factor. In order to reduce this dark current component, a thick (550 Å) undoped GaAs barrier layer is grown next to the top and bottom contact layers.

Figure 8.5 (a) and (b) show the energy band diagram and subband energy states
for this PCSL-QWIP. The intersubband transitions occurs from the highly populated ground heavy-hole state ($E_{HH1}$) to the upper heavy-hole continuum states ($E_{HH3}$ and $E_{HH4}$) for the 8.8 $\mu$m LWIR detection and 5 $\mu$m MWIR detection, respectively. As shown in Fig. 8.5, the combination of type-I (for heavy-hole) and type-II (for light-hole) energy band configurations has three main ingredients to improve the performance of the PCSL-QWIP. First, the mobility of the heavy-holes confined in the ground states (i.e. HH1) of type-I configuration is enhanced by the internal biaxial compressive strain effect, from which a larger normal absorption can be achieved. Second, the heavy-hole excited continuum states (i.e. HH3) are resonant with the GaAs barrier which can maximize the absorption oscillator strength. Finally, the heavy-hole excited continuum states are resonantly lined up with the light-hole states, which may give rise to a strong quantum state coupling effect. It is the resonant-line-up effect that makes the conducting holes behaving like light-holes with high mobility, small effective mass, and long mean free path. Thus, a larger photoconductive gain and a higher photoconductivity are expected in the PCSL-QWIP.

8.4.2. Experiments

In order to measure the device dark current and spectral responsivity of this PCSL-QWIP, a 200$\times$200 $\mu$m$^2$ mesa structure was created by using the chemical etching process. Cr/Au metal films were deposited onto the QWIP mesas with a thickness of about 1500 Å. The substrate of the QWIP device was thinned down to about 50 $\mu$m to partially eliminate the substrate absorption screening effect, and polished to mirror-like surface to reduce the reflection of the normal incident IR radiation.

Figure 8.6 shows the measured dark current at $T = 30$, 60, and 77 K. The device shows the asymmetrical dark current characteristic under the positive and negative bias, which is attributed to the band bending due to dopant migration effect occurred during the layer growth [124]. This PCSL-QWIP is under background
limited performance (BLIP) at $V_b = 0.3 \, \text{V}, 0.7 \, \text{V}$, and $T = 70, 55 \, \text{K}$ respectively, for a field of view (FOV) $90^\circ$.

The responsivity of this QWIP under normal incidence illumination was measured as a function of temperature, bias voltage, and wavelength using a blackbody radiation source and automatic PC-controlled single-grating monochromater system. Two dominant peaks were detected: a twin peak in the LWIR of $\lambda_{p1,2} = 8.9, 8.4 \, \mu\text{m}$ was observed, as shown in Fig. 8.7 (a), and the other is in the MWIR of $\lambda_{p3} = 5.5 \, \mu\text{m}$, as shown in Fig. 8.7 (b). The LWIR twin peaks at $\lambda_{p1,2} = 8.9, 8.4 \, \mu\text{m}$ cover a broad wavelength band from 6.5 to 12 $\mu\text{m}$. Responsivities of 24 mA/W at $V_b = 0.3 \, \text{V}$ and 45 mA/W at $V_b = 0.7 \, \text{V}$ were obtained at $T \leq 75 \, \text{K}$ for the two peak wavelengths. The cutoff wavelength for the LWIR detection band was found to be $\lambda_c \approx 10 \, \mu\text{m}$ with a spectral bandwidth of $\Delta \lambda/\lambda_p = 35 \%$. Detectivity at $\lambda_{p1} = 8.9 \, \mu\text{m}$ was found to be about $4.0 \times 10^9$, $3.2 \times 10^9 \, \text{cm} \cdot \sqrt{\text{Hz/W}}$ at $V_b = 0.3, 0.7 \, \text{V}$ and $T = 75 \, \text{K}$, respectively. These twin peak wavelengths are attributed to the intersubband transition between the confined ground heavy-hole state ($E_{\text{HH1}}$) to the continuum heavy-hole states ($E_{\text{HH3}}$), which is resonantly lined up with the type-II light-hole continuum states, as illustrated in Fig. 8.5. The transition energy for these peak wavelengths is in reasonable agreement with our theoretical calculation. These twin peaks broaden the LWIR detection bandwidth by about a factor of 2. The physical origin for the twin peaks feature is not clear, but a possible explanation may be given as follows. When the continuum HH- and LH-bands are strongly mixed, an individual subband (either HH-band or LH-band) further splits into two subsubband due to the coupling and interaction: one upward and the other downward. This gives rise to the observed twin-peak detection in the LWIR band. The MWIR peak observed at $\lambda_{p3} = 5.5 \, \mu\text{m}$ covering the wavelengths of 4 to 6.5 $\mu\text{m}$. Responsivities for the MWIR band were found to be 7 mA/W, 13 mA/W at $V_b = 0.3, 0.7 \, \text{V}$ and $T = 75 \, \text{K}$, respectively. The spectral bandwidth of $\Delta \lambda/\lambda_{p3} = 27 \%$ was obtained with a cutoff wavelength at $\lambda_c =$
The intersubband transition occurred between $E_{HH1}$ and $E_{HH4}$ subbands was responsible for the MWIR detection. However, no mixing and interaction between HH-band and LH band was observed in this transition. This may be due to the weak overlap interaction at higher subbands. Since $E_{HH2}$ subband is confined inside the quantum wells with very low tunneling probability off the thicker barrier layer, the photoresponse from this heavy-hole state was not detected.

Responsivities versus bias voltage for the LWIR and MWIR peak wavelengths were measured at $T = 75$ K, and the results are shown in Fig. 8.8. The responsivity of $\lambda_{p1} = 8.9 \mu m$ (or $\lambda_{p2} = 8.4 \mu m$) was found to increases linearly with bias voltage for $V_b \leq -1.6 V$ and $V_b \leq +1.2 V$, and then rapidly falls to zero from the peak value with bias interval of 0.15 V. Similar photoresponse was observed for $\lambda_{p3} = 5.5 \mu m$.

It is noted that the responsivity is higher at positive bias than that at negative bias for both MWIR and LWIR bands when $|V_b| \leq 0.5 V$ and then becomes nearly equal for $|V_b| > 0.6 V$. Figure 8.9 shows the photoconductive gain versus bias voltage. A maximum gain of 0.13 was obtained at $V_b = 1.6 V$, and then decreases rapidly for higher bias voltage. The linear photoresponse versus bias voltage is due to the linear photoconductive gain with bias voltage as shown in Fig. 8.9. When the bias voltage increases, the coupling transport breaks down, and then photoconductive gain becomes very small. As a result, no photocurrent was detected for $V_b \leq 1.6 V$. Furthermore, a photovoltaic (PV) response for both MWIR and LWIR bands was also observed for the first time for the p-type QWIP.

8.4.3. Conclusions

In conclusion, we have demonstrated for the first time a new normal incidence p-type compressive strained-layer InGaAs/GaAs QWIP grown on GaAs substrate for the MWIR and LWIR two-band detection. The intersubband absorption and photoresponse in this PCSL-QWIP were enhanced by the biaxial compressive strain in the InGaAs quantum well layers. The improvement in the performance of the
bandwidth and responsivity in this PCSL-QWIP was achieved by using type-I and type-II configuration coupling transport mechanism. Since the total layer thickness of this PCSL-QWIP is greater than the coherent strained-layer limitation, certain strain relaxation might occur, which will result in a larger dark current and lower photoconductive gain than theoretical prediction. By further optimizing the quantum well dopant density, barrier layer thickness, biaxial strain strength, and layer structure parameters, a high performance PCSL-QWIP can be developed for the MWIR and LWIR two-color infrared focal plane arrays image sensor systems with background limited performance (BLIP) at $T = 85 \text{ K}$.
<table>
<thead>
<tr>
<th></th>
<th>type-I</th>
<th>Type-II (Staggered)</th>
<th>Type-II (Misaligned)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td><strong>No Strain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>($a_A = a_B$)</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td><strong>A In Compression</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>($a_A &gt; a_B$)</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>L</td>
<td>H</td>
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<tr>
<td><strong>A In Tension</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>($a_A &lt; a_B$)</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
</tbody>
</table>

Figure 8.1 Schematic illustration of the band-edge lineup in type-I and type-II superlattice. A and B indicate two semiconductor thin layers in the superlattice basis. (C, H, and L indicate conduction, heavy-hole, and light-hole bands, respectively.)
Figure 8.2. Schematic energy band diagram for the p-type tensile strained-layer InGaAs/InAlAs QWIP with consideration of band bending effect. The subband energy levels were calculated to be $E_{LH1} \approx 42$ meV, $E_{HH1} \approx 78$ meV, $E_{HH2} \approx 135$ meV, and $E_{HH3} \approx 198$ meV from the InGaAs quantum well band edge.
Figure 8.3. Measured dark current density and 300-K background photocurrent density for the PTSL-QWIP at FOV = 90°.
Figure 8.4. Normal incidence photocurrents versus wavelength with (a) positive biases and (b) negative biases for the PTSL-QWIP. The insets are the %BLIP at $T = 77$ K.
Figure 8.4. Continued.
Figure 8.5. Schematic energy band diagram (a) and the subband energy levels at zone center as a function of the well width (b) for the In_{0.4}Ga_{0.6}As/GaAs QWIP.
Figure 8.6. Dark current versus bias voltage measured at $T = 30$, 60 and 77 K for the $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$ PCSL-QWIP.
Figure 8.7. Responsivities of (a) $\lambda_{p1,2}$ and (b) $\lambda_{p3}$ versus wavelength with $V_b = 0.3, 0.7$ V at $T = 75$ K.
Figure 8.7. Continued.
Figure 8.8. Responsivities of (a) $\lambda_{p1}$ and (b) $\lambda_{p3}$ versus positive and negative bias at $T = 75$ K.
Figure 8.8. Continued.
Figure 8.9. Photoconductive gain versus bias voltage at $T = 75$ K.
CHAPTER 9
SUMMARY AND CONCLUSIONS

In this work, we have reported the development of several novel III-V semiconductor quantum well infrared photodetectors (QWIPs) using bound-to-miniband (BTM) and bound-to-continuum (BTC) intersubband transition schemes (see Fig. 9.1) for 3-5 μm MWIR and 8-14 μm LWIR detection (see Fig. 9.2). Detectivity in the high $10^9$ to low $10^{12}$ cm$^{-1}$Hz/W has been obtained for these QWIPs at 77 K operation. The unique features for these QWIPs are listed as follows:

- The InGaAs/InAlAs BTM QWIP and GaAs/AlGaAs and GaAs/InGaP BTC QWIPs have PC and PV dual-mode detection characteristics. The PV mode detection for these QWIPs may result from dopant migration effect during the QWIP growth. The BTM intersubband transition is from the highly populated bound ground state in the enlarged quantum wells to the global miniband states formed by the superlattice barrier layers inside the quantum wells. By utilizing resonant tunneling and coherent transport along the superlattice miniband for the BTM QWIP, voltage-tunable spectral bandwidth with $\Delta \lambda / \lambda_p = 7\%$ to $24\%$ has been obtained at peak wavelength 10 μm. A GaAs/AlGaAs QWIP using an enlarged GaAs (110 Å) quantum well with a high dopant density of $5 \times 10^{18}$ cm$^{-3}$ and an enlarged AlGaAs (875 Å) barrier for two-color detection at peak wavelengths of 7.7 and 12 μm has been realized at $T = 77$ K. The detection scheme uses transition from the confined ground-state and the first excited-state inside the enlarged GaAs quantum well to the continuum states slightly above the AlGaAs barrier layers. By using intersubband transition from the first excited states to the continuum states for the PC mode operation, detectivity of $2 \times 10^{10}$ cm$^{-1}$Hz/W is obtained at $\lambda_p = 12 \mu$m, $V_b = 1$ V, and $T = 77$ K.
- The type-II indirect bandgap AlAs/Al_{0.5}Ga_{0.5}As QWIP grown on the (110) GaAs substrate shows normal incidence infrared detection for 2-18 μm wavelength range with six-color response. The intersubband absorption for the normal incidence is created by indirect anisotropic band structure in X-valley and tilted [110] growth direction with respect to the principal of axes of the ellipsoidal valleys. By using X-Γ valley resonant transport mechanism in this type-II QWIP, the enhancement of the photoconductive gain and photoresponsivity has been achieved in both MWIR and LWIR detection bands.

- The p-type tensile strained-layer InGaAs/InAlAs QWIP shows an ultra low dark current density of 7×10^{-7} A/cm² which is about six orders of magnitude smaller than the standard GaAs/AlGaAs QWIP. This QWIP is under background limited performance (BLIP) at λ_p = 8.1 μm for T ≤ 100 K, which is the highest BLIP temperature ever reported. By applying the tensile strain between the quantum well and barrier layer, the light-hole levels are pushed upward and the heavy-hole levels are pulled downward. As a result, the ground heavy- and light-hole states are inverted, and light-hole state becomes the ground bound state in the quantum well. Since the light-hole has a small effective mass, the optical absorption is greatly enhanced. In addition, the p-type compressive strained-layer InGaAs/GaAs QWIP developed in this work has two-color detection at peak wavelengths of 5.5 and 8.9 μm. By applying coupling transport from the heavy-hole type-I states to the light-hole type-II states, large photoresponse is achieved.

Table 9.1 summarizes the peak and cutoff wavelengths, responsivities, detectivities, and background limited performance temperatures for the QWIPs studied. The background limited performance temperatures T_{BLIP} range from 45 K up to 100 K. The p-type tensile strained-layer InGaAs/InAlAs QWIP has the highest BLIP temperature with T_{BLIP} ≤ 100 K, whereas n-type unstrained InGaAs/InAlAs QWIP
has the lowest BLIP temperature with $T_{BLIP} \sim 45$ K. The dark current densities for some of the QWIPs studied and a standard GaAs/AlGaAs QWIP at $T = 77$ K are summarized in Fig. 9.3. The dark current densities of the n-type VT- and type-II QWIPs are found to be about one order of magnitude lower than that of the standard GaAs/AlGaAs QWIP, whereas the dark current density of the n-type DM-QWIP is found to be about two orders of magnitude lower than that of the standard GaAs/AlGaAs QWIP due to the incorporation of the enlarged AlGaAs barrier layers in the DM-QWIP.

All QWIPs studied here QWIPs have not been optimized with respect to the layer thickness, doping profile, structure growth condition, and the number of quantum well period. Optimization of these QWIPs can further improve the quantum efficiency and reduce the dark current. In view of the advantages such as high growth uniformity, flexible spectral response tunability, and mature processing technologies in the III-V materials over the HgCdTe, large-area and high-quality QWIP imaging sensor arrays can be fabricated for a wide variety of applications in the atmospheric spectral window of 3-5 $\mu$m and 8-14 $\mu$m.
Table 9.1. Summary of the peak and cutoff wavelengths, responsivities, detectivities, and BLIP temperature for the developed QWIPs.

<table>
<thead>
<tr>
<th>QWIP</th>
<th>$\lambda_p$ (µm)</th>
<th>$\lambda_c$ (µm)</th>
<th>R (A/W)</th>
<th>$D^*$ (cm-$\sqrt{Hz}$/W)</th>
<th>$T_{BLIP}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM</td>
<td>12 (PC)</td>
<td>13.2</td>
<td>0.48</td>
<td>$2.0 \times 10^{10}$</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>7.7 (PV)</td>
<td>8.5</td>
<td>11,000 (V/W)</td>
<td>$1.5 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>VT</td>
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<tr>
<td>PV</td>
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<td>1,000 (V/W)</td>
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<td>900 (V/W)</td>
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Figure 9.1. Schematic energy-band diagrams for these QWIPs developed in this work.
(a) Energy band diagram for a 
GaAS(110Å QW)/AlGaAs(875Å BA) 
DM-QWIP.

(b) Energy band diagram for an InGaAs 
(110Å QW)/InAlAs-InGaAs(30-46Å SL) 
VT-QWIP.

(c) Energy band diagram for a 
GaAs(50Å QW)/InGaP(360Å BA) 
PV-QWIP.

Figure 9.1. Continued.
Figure 9.2. Normalized responsivities of (a) the 3-5 μm MWIR and (b) the 8-14 μm LWIR detection bands for these QWIPs developed in this work.
Figure 9.3. Dark current densities for these QWIPs developed in this work.
APPENDIX A
ENERGY DISPERSION EQUATION FOR SUPERLATTICE

By using the transfer matrix method, the energy dispersion equations for periodic structures such as multiple quantum wells and superlattices can be deduced [125]. It is assumed that each layer contains sufficient number of atomic sublayers (i.e. monolayers) so that the effective-mass model holds for the calculation. From the effective-mass model by using the effective mass envelope function approach, the solution of the conduction band envelope function for j-th region, \( \phi_j \), can be obtained from

\[
\phi''_j + k_j^2 \phi_j = 0, \tag{A.1}
\]

where \( k_j \) is the wave propagation constant, \( k_j = \sqrt{\frac{2m_j^* (E - V_c)}{\hbar^2}} \), \( V_c \) conduction-band minimum energy referred to the valence-band maximum of the quantum well, and \( E \) the electron energy along the superlattice growth direction. When \( k_j \) is either real or imaginary, the equation gives either oscillatory or evanescent wave solution, respectively. For the one-band model and a flat-band condition, the functions of \( \phi_j \) and \( \phi'_j / m_j^* \) should be continuous across the heterointerfaces. These two continuous functions at the heterointerfaces can be expressed by a \( 2 \times 1 \) matrix, which is also called transfer vector,

\[
S = \begin{pmatrix}
S_1 \\
S_2
\end{pmatrix} = \begin{pmatrix}
\phi_j \\
\phi'_j / m_j^*
\end{pmatrix} \tag{A.2}
\]

On the other hand, the wave conduction property through the multiple quantum wells or superlattice system can be also represented by the transmission line concepts with the transfer impedance \( Z_j = S_1 / S_2 \) and the characteristic impedance \( Z^* = m^* / k_j \). The energy dispersion can be obtained by setting the total impedance equal to 0 or \( \infty \).
For a superlattice with the basis $L$, the wave transfer equation is given by $[S]_{z+L} = [T][S]_z$, where $[T]$ is the transfer matrix (i.e., the transfer matrix of a superlattice is for one period of the superlattice). If one period of the superlattice consists of $N'$ sublayers, then $[T]$ is given by

$$
T = \begin{pmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{pmatrix} = \prod_{j=1}^{N'} \begin{pmatrix}
\cos k_j L_j & Z_j \sin k_j L_j \\
-\frac{1}{2} \sin k_j L_j & \cos k_j L_j
\end{pmatrix},
$$

(A.3)

where $L_j$ is the thickness of a layer in one period of the superlattice. The dispersion equation for the system is readily found to be,

$$T_{11} + T_{22} = 2 \cos k_z L,
$$

(A.4)

where $k_z$ is the superlattice wave vector, $L$ the period of the superlattice ($= \sum_{j=1}^{N'} L_j$). The conduction band nonparabolicity, bias-dependent property, and coupling between $X$-band and $\Gamma$-band could be also included in the transfer matrix expression to give a complicated energy dispersion relation.

When an electric field $F$ is applied on the superlattice, the conduction band $V_c$ is tilted to be $V_c(z) = V_c - eFz$, and Eq. (A.1) and the transfer vector are changed. The transfer matrix elements $T_{ij}$ are the linear combination of the Airy functions.

For the two-band and three-band models, the transfer vectors, wave vectors, transfer matrices, and dispersion relation are the same as the one-band results except that the effective mass $m_j^*$ for $j$-th layer in the superlattice is replaced by,

$$m_j^* = \frac{m_o^*}{(1 - \gamma)E_{go}}(E - V_{LH_j})
$$

(A.5)

for the two-band model (i.e., conduction and light-hole bands), and

$$m_j^* = \frac{m_o^*}{(1 - \gamma)E_{go}} \frac{3E_{go} + 2\Delta_o}{E_{go} + \Delta_o} \frac{(E - V_{SO,j})(E - V_{LH,j})}{2(E - V_{SO,j}) + (E - V_{LH,j})}
$$

(A.6)

for the three-band model (i.e., conduction, light-hole, and split-off bands), where $m_o^*$, $E_{go}$, $\gamma$, and $\Delta_o$ are the effective mass, energy bandgap, effective mass ratio (i.e.,
\( m^*/m_0, m_0 \) free electron mass), and split-off energy for the quantum well, respectively. \( V_{LH} \) and \( V_{SO} \) are the light-hole band and split-off band maximum (referred to the quantum well valence band maximum), respectively. It is noticed that the effective masses of the electrons for both two-band and three-band models depend not only on the coupling effects among S-type conduction band and P-type valence bands, but also on their energy magnitude.

All above dispersion relations for the one-band, two-band, or three-band models are valid only for near \( \Gamma \)-point or X-point single valley quantum well/superlattice structures. However, in the multivalleys quantum well/superlattice structures such as \( \Gamma \)-X interaction (or coupling) in a type-II structure, the above simple envelope function approach breaks down since the coupling of their Bloch functions between the host materials cannot be neglected. Due to the lack of the translational symmetry at the interfaces in the \( \Gamma \)-X coupling superlattice, \( \Gamma \)-X valleys can couple with each other, and the electron states at the interfaces are a mixture of the zone-center \( \Gamma \) and zone-edge X related bulk states. The wave function \( \psi \) is a mixed-symmetry form, and is written as the sum of the products of slowly varying envelope functions \( \phi_n \) and Bloch functions \( \phi_B \) for \( \Gamma \)-valley and X-valley,

\[
\psi = (\phi_n\phi_B)_\Gamma + (\phi_n\phi_B)_X. \tag{A.7}
\]

On the other hand, the wave function \( \psi \) can be written in the vector notation,

\[
\psi = \begin{pmatrix} \psi_\Gamma \\ \psi_X \end{pmatrix}. \tag{A.8}
\]

The elastic intervalley interactions are possible only between the \( \Gamma \) minimum and \( k_z \) direction of the X-minima due to the potential discontinuity in \( k_z \) direction of X-minima. The lateral \( k_x \) and \( k_y \) momenta in the X-minima do not play roles in the intervalley interaction (or mixing) because of their momentum conservation requirement in the quantum well/superlattice structure. The lateral interaction may be activated if the heterointerface roughness is taken into the consideration or the
superlattice layers are grown on a tilted direction with respect to principal axes of ellipsoidal energy surface in X-valley. The transfer potential energy $V_{\Gamma X}$ for the intervalley interaction can be expressed by [101],

$$V_{\Gamma X} = \begin{pmatrix} V_\Gamma & \alpha \delta(z) \\ \alpha \delta(z) & V_X \end{pmatrix} \quad (A.9)$$

where diagonal terms $V_\Gamma$ and $V_X$ are the energy band offset potential for $\Gamma$ and $X$ valleys, respectively, and off-diagonal elements $\alpha \delta(z)$ model the $\Gamma$-$X$ coupling strength at the interfaces. $\alpha$ is the coupling constant (typical value $0.1 \sim 0.2 \text{eVÅ}$), and $\delta(z)$ is the Dirac delta function. The effective mass Hamiltonian is,

$$H = \begin{bmatrix} -\frac{\hbar^2}{2} \frac{\partial}{\partial z} \frac{\partial}{\partial z} & 0 \\ 0 & -\frac{\hbar^2}{2} \frac{\partial}{\partial z} \frac{\partial}{\partial z} \end{bmatrix} + \begin{bmatrix} V_\Gamma & \alpha \delta(z) \\ \alpha \delta(z) & V_X \end{bmatrix}. \quad (A.10)$$

By using the wave function connection rules across the interface, the coupled wave functions $\psi$ can be obtained with using experimentally-determined coupling constant $\alpha$.

The dispersion relation for the coupling system can also be calculated by using the transfer matrix method. If the transfer vector notation is used in the $\Gamma$ valley and $X$ valley wave functions, then transfer vector $[S_\Gamma]$ and $[S_X]$ are expressed by,

$$S_\Gamma = \begin{pmatrix} \psi_\Gamma \\ \psi'_\Gamma \\ m_\Gamma \end{pmatrix}; S_X = \begin{pmatrix} \psi_X \\ \psi'_X \\ m_X \end{pmatrix}. \quad (A.11)$$

The uncoupled elements $[T_\Gamma]$ and $[T_X]$ of the transfer matrices for $\Gamma$-$X$ coupled quantum well/superlattice have the similar form as Eq. (A.3), whereas the coupled elements $[T_{\Gamma X}]$ are,

$$T_{\Gamma X} = T_{X \Gamma} = \begin{pmatrix} 0 & 0 \\ 0 & \frac{2\pi}{\hbar^2} \end{pmatrix}. \quad (A.12)$$

The total transfer matrix becomes a $4 \times 4$ matrix, and the overall transfer equation is written as,

$$\begin{bmatrix} S_\Gamma \\ S_X \end{bmatrix}_{x+L} = \begin{pmatrix} T_\Gamma & T_{\Gamma X} \\ T_{X \Gamma} & T_X \end{pmatrix} \begin{pmatrix} S_\Gamma \\ S_X \end{pmatrix}_x. \quad (A.13)$$
The allowed minibands occur at the energies where the eigenvalues of $[T]$ have absolute values equal to one. When the coupling interaction from light-hole band and split-off band becomes important in addition to the intervalley coupling, the uncoupled transfer elements $[T_T]$ and $[T_X]$ for the two-band or three-band model should be used, and then the $4 \times 4$ transfer matrix can still give reasonable miniband structures.
APPENDIX B
OPTICAL MATRIX FOR STRAINED-LAYER SUPERLATTICE

The optical matrix elements $|\mathbf{e} \cdot \mathbf{P}_{ij}|$ can be obtained from the $k.p$ matrix elements, which have the same form as the $k.p$ matrix elements except that $k_ik_j$ is replaced with $k_i\epsilon_j + k_j\epsilon_i$ and multiplied by a constant factor $m_0/h$ [118]. The $3 \times 3$ optical matrix elements are given as follows:

$$
\frac{m_0}{h} \begin{bmatrix}
T_{HH} & T_{HL} & T_{HS} \\
T_{LH} & T_{LL} & T_{LS} \\
T_{SH} & T_{SL} & T_{SS}
\end{bmatrix}
$$

(B.1)

where the $T_{ij}$ are given by

$$
T_{HH} = 2(A - B)\epsilon_z k_z + (2A + B)(\epsilon_x k_x + \epsilon_y k_y), 
$$

(B.2)

$$
T_{LL} = 2(A + B)\epsilon_z k_z + (2A - B)(\epsilon_x k_x + \epsilon_y k_y), 
$$

(B.3)

$$
T_{SS} = 2A(\epsilon_z k_z + \epsilon_x k_x + \epsilon_y k_y), 
$$

(B.4)

$$
T_{HL} = \frac{j}{\sqrt{3}} N(\epsilon_x \cos \eta - \epsilon_y \sin \eta)k_z - \frac{j}{3} N \epsilon_z k_{||}
- \sqrt{3}B(\epsilon_x k_x - \epsilon_y k_y) \cos \chi 
+ \frac{1}{\sqrt{3}} N(\epsilon_x k_y + \epsilon_y k_x) \sin \chi, 
$$

(B.5)

$$
T_{HS} = \frac{1}{\sqrt{6}} N(-\epsilon_x \cos \eta + \epsilon_y \sin \eta)k_z + \frac{1}{6} N \epsilon_z k_{||}
+ j\sqrt{6}B(\epsilon_x k_x - \epsilon_y k_y) \cos \chi 
- \frac{2}{\sqrt{6}} N(\epsilon_x k_y + \epsilon_y k_x) \sin \chi, 
$$

(B.6)

$$
T_{LS} = \left[ j2\sqrt{2}B\epsilon_z + \frac{1}{\sqrt{2}} N \epsilon_x \cos(\chi - \eta) - \epsilon_y \sin(\chi - \eta) \right] k_z 
- j\sqrt{2}B(\epsilon_x k_x + \epsilon_y k_y) 
- \frac{1}{\sqrt{2}} N \epsilon_z k_{||} \cos(\chi - 2\eta), 
$$

(B.7)
\[ T_{SH} = T_{HS}^* , \quad \text{(B.8)} \]
\[ T_{SL} = T_{LS}^* , \quad \text{(B.9)} \]
\[ T_{LH}^* = T_{HL}^* . \quad \text{(B.10)} \]

Here \( A, B, N, \eta, \) and \( \chi \) are the inverse mass band parameters [118].
REFERENCES


BIOGRAPHICAL SKETCH

Yanhua Wang was born in Kang-ping County, Liaoning Province, P. R. of China, on September 3, 1955. He received a Bachelor of Science degree from the Department of Physics of Liaoning University in 1982. After graduation, he worked in the university as a research assistant from 1982 to 1987.

In March of 1987, he came to the University of Florida as a visiting scholar engaged in research on the topic of equivalent circuit modeling of recombination processes in semiconductors. In July of 1988, he enrolled in the Graduate School of the University of Florida, in the Department of Electrical Engineering. After receiving a Master of Science degree in December 1990, he began his Ph.D. research on the development of III-V quantum well infrared photodetectors in the Electrical Engineering Department of the University of Florida.
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