Enhancement of the Stark effect in AlInAs/GaInAs coupled quantum wells and their application to tunable midinfrared photodetectors

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A tunable midinfrared photodetector using 1→4 intersubband Stark shift in the four-level AlInAs/GaInAs coupled quantum wells (CQWs) is proposed. The operation of this device is based on the infrared absorption by the electrons in the ground state transited from the ground-state subband \( E_1 \) of the CQWs to the third-excited-state subband \( E_4 \). A large variation of eigenenergy spacing \( \Delta E_{41} \) between \( E_1 \) and \( E_4 \) under an applied electric field can be achieved for the proposed AlInAs/GaInAs CQW system. Since the infrared radiation is absorbed via the intersubband resonance absorption \( (\hbar \omega = E_4 - E_1) \), the detected infrared wavelength can be tuned by the spacing \( \Delta E_{41} \) which can be adjusted by an applied electric field. The tunability of these AlInAs/GaInAs CQWs have been studied theoretically. Based on theoretical calculations, tuning ranges from 3 to 3.9 and 2.9 to 4.2 \( \mu m \) are predicted for the proposed asymmetric CQW structure and compositionally asymmetric CQW structure, respectively. This tuning capability is achieved by varying the applied electric field in the 90 to \(-90\) kV/cm range.

I. INTRODUCTION

Quantum confinement of carriers in a semiconductor quantum well leads to the formation of discrete subbands. Transition between these subbands of the quantum well has extremely large oscillator strength and relatively narrow linewidth.\(^1\) The linear intersubband optical absorption of the quantum well has been studied experimentally and a very large and sharp optical-phonon-absorption resonance between the ground state and the first excited state of modulation-doped AlGaAs/GaAs multiexcitonic quantum wells have been observed.\(^2\)-\(^6\)

Up to now, novel infrared detectors based on the intersubband absorption in the doped single-quantum-well superlattice have been fabricated to replace the conventional HgCdTe photodetector.\(^7\)-\(^13\) Since the thickness and the composition of these single quantum wells can be chosen to produce only two subbands in the well with an eigenenergy spacing close to 155–103 meV, this system will be useful for the detector application in the \( \lambda = 8–14 \) \( \mu m \) atmospheric window spectral region. Studies of the intersubband absorption have also been conducted in the lattice-matched quantum-well superlattices of \( Al_{0.48}In_{0.52}As/Al_{0.47}Ga_{0.53}As \) grown by using molecular-beam epitaxy (MBE) on InP substrates.\(^14\)-\(^19\) Since the AlInAs/GaInAs heterostructure has a larger conduction-band offset \( (\Delta E_c \approx 550 \text{ meV}) \) compared to the AlGaAs/GaAs material system, it is a promising candidate for the midinfrared detector operating in the 3–5 \( \mu m \) atmospheric window spectral region; however, it is difficult to fabricate a voltage tunable photodetector by using these doped single-quantum-well superlattices because there are no evidence of the Stark shift for all of these quantum-well structures. Currently, there is considerable interest in the development of highly sensitive tunable infrared detectors. The Stark shift of intersubband energy level of a square quantum well has been studied and the resulting shift compared to the peak width is rather small for the practical tunable detector application.\(^20\)-\(^22\)

By employing the large conduction-band offset of the AlInAs/GaInAs material system and the enhanced Stark effect of the coupled-quantum-well (CQW) structure, a tunable midinfrared photodetector is proposed in this article. The CQW structure (shown in Fig. 1) consisted of a pair of quantum wells separated by a barrier (about 30 \( \AA \)) narrow enough that considerable interaction occurs between electronic states in these two adjacent wells. In this way, the electron in each well can interact strongly with each other to achieve a large Stark tuning effect. Very strong Stark shifts of intersubband transition in this quantum-well structure have been predicted theoretically\(^23\)-\(^29\) and observed experimentally.\(^30\)-\(^33\) This large Stark shift of energy separation can be used to tune the resonance absorption and the device acts like a voltage tunable photodetector.

The AlInAs/GaInAs CQWs which have four confined states in the well are used to design the tunable midinfrared photodetectors for both ultralow-loss fiber communications systems and infrared systems operating at \( \lambda = 3–5 \) \( \mu m \) atmospheric window. The operation of this device is based on the infrared absorption by the electrons in the ground state transited from the ground-state subband \( E_1 \) of the CQWs to the third-excited-state subband \( E_4 \). A large variation of eigenenergy spacing \( \Delta E_{41} \) between \( E_1 \) and \( E_4 \) under an applied electric field can be achieved for the proposed AlInAs/GaInAs CQW system. Since the infrared radiation is absorbed via theintersubband resonance absorption \( (\hbar \omega = E_4 - E_1) \), the detected infrared wavelength can be tuned by the spacing \( \Delta E_{41} \) which can be adjusted by an applied electric field. The tun-
ability of these AlInAs/GaInAs CQWs have been studied theoretically in this article. The theoretical calculations show that AlInAs/GaInAs CQWs do give good tunability in the midinfrared range. For the symmetric CQW structure, an applied bias positive or negative can only induce a blue Stark shift in the intersubband absorption. The subband spacing $\Delta E_{41}$ could be tuned in one direction only and give a smaller tuning range. In contrast, both red and blue Stark shifts of the intersubband resonance absorption under the applied electric field are possible for the asymmetric CQWs and the compositionally asymmetric CQWs. Thus, a much larger tunability can be achieved for these two kinds of asymmetric CQW structure. Based on theoretical calculations, tuning ranges from 3 to 3.9 and 2.9 to 4.2 $\mu$m are predicted for the asymmetric CQW structure and compositionally asymmetric CQW structure, respectively. This tuning capability is achieved by an applied electric field in the 90 to $-90$ kV/cm range.

In order to supply the electron to the ground state, the well must be doped with an $n$-type dopant. In this study, only the wider left-hand-side well of the CQW is assumed to be doped with silicon (the doping concentration is about $5 \times 10^{17}$ cm$^{-3}$). Under the influence of the ionization donor density, subband envelope wave functions and eigenenergies are calculated self-consistently by simultaneously solving the one-dimensional Schrödinger equation and Poisson's equation. The Schrödinger equation is solved by the transfer-matrix method and Poisson's equation by the numerical integration. The energy-dependent effective mass due to energy-band nonparabolicity is also taken into account in Ref. 34. This analysis is then employed to determine the energy-band nonparabolicity induced lowering of the subband eigenenergies.

This article is organized into four sections including the introduction and the conclusion. In Sec. II, a theoretical basis for the calculation is laid. In Sec. III, graphs from numerical calculations are presented along with discussions.

II. THEORY AND FORMALISM

In this section, a self-consistent method to evaluate the envelope wave functions and the potential profile is described for CQW structures under the influence of an applied electric field and ionized donor. The results of the derivation are essential to understand the physical properties of electrons in these quantum-well structures and the characteristics of the infrared detectors employing these quantum-well structures.

The CQW generally refers to a structure where a thin barrier layer is sandwiched between two wells. Since this barrier is very thin, there is an appreciable interaction among electron states in these two wells. Depending on the width and composition difference of these two wells, the CQW system can be divided into three different categories: symmetric CQWs (Fig. 1), asymmetric CQWs (Fig. 2), and compositionally asymmetric CQWs (Fig. 3).
eigenenergies of the one-dimensional finite potential well can be found by solving the time-independent Schrödinger equation,

$$\hat{H}\psi = \left(-\frac{\hbar^2}{2m^*} \frac{d^2}{dz^2} + U(z)\right)\psi = E\psi,$$

(1)

where $U(z) = -qV(z)$ represents the electronic potential energy variation, $m^*$ is the effective mass of the charge particle, and $\hbar=h/2\pi$, where $h$ is Plank’s constant. $E$ and $\psi$ respectively, represent the energy eigenvalue and the eigenfunction of the bound state. At the AlInAs/GaInAs interface, the electronic wave function and its first derivative $\psi'(z)/m^*$ are assumed to satisfy the continuity condition. The electrostatic potential $V(z)$ in the conduction band is determined by Poisson’s equation,

$$\frac{d^2V(z)}{dz^2} = -\frac{q}{\epsilon} [N_D^+(z) - n(z)],$$

(2)

where $N_D^+(z)$ is the ionized donor concentration and $n(z)$ is the electron density. To solve the Schrödinger equation and the Poisson’s equation self-consistently, an initial potential profile is first guessed. The Schrödinger equation was solved by the transfer-matrix method to find eigenenergies and envelope wave functions for the given potential profile. The Poisson’s equation was then solved by the numerical integration to find the new potential profile for the known two-dimensional electron gas (2DEG) profile from the Schrödinger equation. This process is repeated until the convergence criterion $|V(z)_{i+1} - V(z)_{i}| / V(z)_{i} < \delta$ is reached, where $V(z)$ is the trial potential profile, $V(z)_{i+1}$ is the resulting potential profile, and $\delta$ is a small number. The energy-dependent effective mass due to the energy-band nonparabolicity has also been taken into account. This causes a lowering of subband energies of higher-excited-state subbands and the lowering effect becomes substantial for the highest-excited-state subband. For a more detailed derivation, most materials can be found in Refs. 29 and 33.

Based on the density matrix formalism, the linear intersubband optical-absorption coefficient within the conduction band of the quantum well can be expressed as

$$\alpha(\omega) = \omega \left(\frac{\mu_0}{\epsilon}\right)^{1/2} \left(\frac{m^*K_BT}{w\pi\hbar^2}\right) \times \sum_{m,n=1}^{4} \left[ M_{mn} \right] \ln \left[ \frac{1 + \exp[(E_F-E_m)/K_BT]}{1 + \exp[(E_F-E_n)/K_BT]} \right] \times \frac{\hbar}{\tau} \left(\frac{E_m-E_n-\hbar\omega}{2+(\hbar/\tau)^2}\right),$$

(3)

where $\mu_0$ is the permeability in vacuum, $\epsilon$ is the dielectric constant, $w$ is the total quantum-well width, $\tau$ is the dephasing time, $E_F$ is the Fermi level of the system, $K_B$ is the Boltzmann constant, $T$ is the temperature, $E_n$ and $E_m$ are the eigenenergies with $m>n$. The dipole matrix element $M_{mn}$ is given by

$$M_{mn} = \int_{-w/2}^{w/2} \psi_m^*(z)ez\psi_n(z)dz.$$

III. RESULTS AND DISCUSSION

The mathematical method to find the eigenenergies and envelope wave functions of the Schrödinger equation for various CQW structures with applied electric field has been developed in Sec. II. The theories for the absorption coefficient have been also studied. Based on these theories, numerical results and discussions are presented in this section. All the numerical calculations done in this article are based on the following parameters unless otherwise stated: The doping concentration is assumed to be $5\times10^{17}$ cm$^{-3}$, the central barrier width is 30 Å, $T=77$ K, and all of the dephasing times $\tau$ are assumed to have the same value of 0.14 ps. The conduction-band-gap discontinuity and effective mass $m^*$ for the AlInAs/GaInAs material system used here are adopted from Ref. 17.

A. Symmetric CQW systems

The band diagram and envelope wave functions of a symmetric CQW without applied electric field are shown in Fig. 1. The relation of the subband eigenenergies and the eigenenergy difference $\Delta E_{41}$ between the ground-state subband $E_1$ and the third-excited-state subband $E_4$ as a function of the applied electric field for the symmetric CQW.

It can easily be seen that the resonance absorption occurs at $\hbar\omega = E_m - E_n$. Since $E_4 - E_1$ increases with an applied electric field for the CQWs, the absorption resonance can be easily tuned by the external electric field for these CQW structures.

![Figure 4](image-url)

FIG. 4. Relation of the subband energies and the eigenenergy difference $\Delta E_{41}$ between the ground-state subband $E_1$ and the third-excited-state subband $E_4$ as a function of the applied electric field for the symmetric CQW.
CQW becomes evident. It is clear that the center of gravity for electron density of the odd-state subbands ($E_1$ and $E_3$) and those of the even-state subbands ($E_2$ and $E_4$) tend to shift oppositely in the presence of an electric field. The electrons residing in the ground-state subband and the third-excited-state subband are further separated by an additional amount of potential energy difference due to the applied electric field. This additional separation will give an additional eigenenergy difference $\Delta E_{41}$. Thus, the CQWs do give an enhanced Stark effect.

From Fig. 4, it is evident that both the applied positive electric field and negative electric field can only induce blue Stark shift in the intersubband absorption energy $\Delta E_{41}$ due to its symmetric band structure. Thus, the subband spacing $\Delta E_{41}$ of the symmetric CQWs could be tuned in one direction only and give a smaller tuning range. The small asymmetry for the profile of the $\Delta E_{41}$ about the zero applied-electric-field line on Fig. 4 is the result of the doping asymmetry in the CQW where only the left-hand-side well is assumed to be $n$-type doped.

B. Asymmetric CQW system

The tuning range of CQWs can be further enhanced by employing the structure which have blue and red Stark shift effect. In order to have both blue and red Stark shift, the CQWs must be asymmetric about the direction of the applied electric field. This can be accomplished by the following two methods: (1) the use of a narrow well (asymmetric CQWs) and (2) the use of a shallow well (compositionally asymmetric CQWs). A schematic band diagram of an asymmetric CQW without applied electric field is shown in Fig. 2. The variation of the subband eigenenergies and the eigenenergy difference $\Delta E_{41}$ as a function of the applied electric field is shown in Fig. 6. It is evident that the intersubband transition $\Delta E_{41}$ in this CQW structure can either be red or blue Stark shifted depending on the direction of the applied electric field. The blue shift occurs as the applied electric field is positive. The red shift occurs as the applied electric field is negative. Thus, the corresponding subband spacing $\Delta E_{41}$ can be tuned in a wider range by the applied electric field. The amount of shift is about 100 meV as the applied electric field varied from $-90$ to $90$ kV/cm.

The absorption coefficient can be evaluated by using Eq. (3). In Fig. 7, the relation between the absorption coefficient and the applied electric field is plotted for the asymmetric CQW structure. It can be seen that this structure does give a very good tunability. The spectral response of the proposed asymmetric CQW is from $3$ to $3.9$ $\mu$m as the electric field varies from $90$ to $-90$ kV/cm.

C. Compositionally asymmetric CQW system

The band diagram and envelope wave functions of a compositionally asymmetric CQW without applied electric field are shown in Fig. 3. The compositionally asymmetric CQW consists of a pair of quantum wells with different depth separated by a thin barrier. The depth of each quantum well can be controlled by the composition of the quantum well.

FIG. 5. Electronic potential energy profile $U(z)$ for the symmetric CQW structure under the applied electric field of 50 kV/cm.

FIG. 6. Relation of the subband energies and the eigenenergy difference $\Delta E_{41}$ between the ground-state subband $E_1$ and the third-excited-state subband $E_4$ as a function of the applied electric field for the asymmetric CQW.

FIG. 7. Calculated linear intersubband absorption coefficient $\alpha$ as a function of infrared wavelength under various applied electric fields for the asymmetric CQW.
CQW tunable photodetectors with tuning ranges from 3 to the CQW photodetectors has been studied. An AlInAs self-consistent method, and the absorption coefficiency of no evidence of the Stark shift, and absorption resonance can-
well. In this study, a Ga$_x$In$_{1-x}$As layer is assigned as the deep quantum and a Ga$_y$In$_{1-y}$As layer is used as the shallow quantum well with $x<y$. By introducing this difference in the quantum well depth $\Delta U$, the compositionally asymmetric CQWs are an asymmetric system even with equal quantum-well width. The compositionally asymmetric CQW with this extra design parameter of the $\Delta U$ is rendered much more flexible in customizing the subband eigenenergy levels and the electronic envelope wave functions. Both the eigenenergy of the ground state $E_1$ and the second excited state $E_3$ are nearly independent on the $\Delta U$ while the eigenenergy of the first excited state $E_2$ and the eigenenergy of the third excited state $E_4$ are raised with the $\Delta U$. In this way, the third-excited-state subband $E_4$ can be lifted to the conduction-band edge of the sidewall by increasing $\Delta U$ to further increase the transmission probability of the photoexcited electrons. Thus, these CQW structures can be designed to detect even shorter-wavelength infrared radiation while retain a good tunability. The peak absorption wavelength versus the applied electric field for the 70-30-47 with $\Delta U=60$ meV and 61-30-58 with $\Delta U=185$ meV compositionally asymmetric CQWs are plotted in Figs. 8 and 9, respectively. Tuning ranges are from 3 to 4 and 2.9 to 4.2 $\mu m$, respectively, have been proposed. These photodetectors are ideal for the 3–5 $\mu m$ atmospheric spectral window and for the application in long-distance fiber communications. Furthermore, the application of this enhanced Stark effect of the CQWs is not limited to tunable photodetectors. For example, the modulator can be a good area for possible application of this enhanced Stark effect.

IV. CONCLUSIONS

Conventional multiquantum-well photodetectors show no evidence of the Stark shift, and absorption resonance cannot be tuned by the applied electric field. Coupled quantum wells with a large Stark effect can be used to fabricate tunable photodetectors. The tunability has been estimated by the self-consistent method, and the absorption coefficieny of the CQW photodetectors has been studied. An AlInAs/GaInAs asymmetric CQW and compositionally asymmetric CQW tunable photodetectors with tuning ranges from 3 to 3.9 and 2.9 to 4.2 $\mu m$, respectively, have been proposed. These photodetectors are ideal for the 3–5 $\mu m$ atmospheric spectral window and for the application in long-distance fiber communications. Furthermore, the application of this enhanced Stark effect of the CQWs is not limited to tunable photodetectors. For example, the modulator can be a good area for possible application of this enhanced Stark effect.

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