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Very large Stark shift in three-coupled-quantum wells and their application to tunable far-infrared photodetectors

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The quantum-confined Stark effect in the three-coupled-quantum-well (TCQW) structure is studied theoretically in this paper. The basic TCQW structures are composed of three quantum wells separated by two thin barriers. Coupled one-dimensional Schrödinger and Poisson equations are solved self-consistently to find the sub-band eigenenergies and the envelope wave functions for the TCQW structures. Results indicate that the GaInAs/AlGaAs/GaAs two-depth TCQW structure exhibits both a very large Stark shift and a high absorption coefficient for the 1→3 intersub-band transition. By using a 1→3 intersub-band Stark shift in the two-depth TCQW structure, a highly sensitive tunable far-infrared photodetector is proposed. This photodetector is ideal for device applications in the 8–14 μm atmospheric window region. The operation of this device is based on the infrared absorption by electrons in the ground state transited from the ground-state sub-band E1 of the TCQW to the second-excited-state sub-band E3. A very large variation of eigenenergy spacing ΔE31 between E3 and E1 under an applied electric field can be achieved. Since the infrared radiation is absorbed via the intersub-band resonance absorption (ℏω=E3−E1), the detected infrared wavelength can be tuned by the ΔE31 which can be adjusted by an applied electric field. Based on the theoretical calculations, a tuning range from 7.4 to 14 μm is predicted for the two-depth TCQW structure. This tuning capability is achieved by varying the applied electric field in the 60 to −60 kV/cm range. © 1995 American Institute of Physics.

I. INTRODUCTION

There has been a growing interest recently in fundamental studies of quantum-well structures under the application of an electric field perpendicular to the layers. The most extensively studied and utilized subject is the quantum-confined Stark effect which generally refers to a shift in the eigenenergy levels of the quantum well under an applied electric field. The eigenenergy levels for a charge particle in a quantum well may undergo significant shifts in the presence of an external electric field, and these shifts will have important effects on the optical and electronic properties of quantum-well structures. In particular, the optical properties in quantum-well structures are strongly field dependent. The potential applications are infrared photodetectors with high wavelength selectivity based on the intersub-band absorption, high contrast-ratio optical modulators, and voltage-controllable nonlinear optical devices.

Currently, there is considerable interest in the development of highly sensitive tunable infrared photodetectors. The Stark shift of the intersub-band 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 photodetector application. From the device point of view, it is desirable to have quantum-well structures with a high absorption coefficient and a large Stark shift under low driving bias. Studies of the intersub band Stark shift have also been conducted in the step quantum well instead of the single-quantum well, in which an order-of-magnitude-larger Stark shift has been predicted and observed. However, an increasing amount of interest has been devoted to studying more sophisticated quantum-well structures, such as coupled-quantum wells (CQW). The CQW structures (as shown in Fig. 1) generally consisted of a pair of quantum wells separated by a thin barrier. Large Stark shifts of the intersub-band transition in this quantum-well structure have been predicted theoretically and observed experimentally. 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 enhanced Stark effects of the AlGaAs/GaAs CQW structures and their application to tunable far-infrared photodetectors have been discussed. To optimize the CQW voltage-tunable detectors, the relevant eigenenergy spacing ΔE21 in the CQW should be tuned in a broader range by the applied electric field and the corresponding transition dipole matrix element should be maximized. There are two contribution sources for the ΔE21, the initial zero-field separation ΔE0 and the field-induced Stark separation ΔEz. As shown in Fig. 1, the ground-state sub-band electrons are mainly located in the wide well and the first-excited-state sub-band electrons in the narrow well; thus ΔEz can be approximated as the potential drop between the centers of these two wells. In order to have a high sensitivity of ΔEz with an applied electric field, these two quantum wells should be separated as far as possible and the middle barrier thickness should be made as large as possible. However, a very thick middle barrier will prevent coupling of electrons between these two adjacent quantum wells, the CQW becomes a two-uncoupled-single-quantum well, and ΔE21 cannot be tuned any further. Thus there will be some optimum choice for the

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middle barrier thickness and the amount of Stark shift is limited by this middle barrier thickness.

In order to have a larger Stark shift while maintaining strong coupling between these two wells, a quantum well is used to replace the middle barrier. In this way, a three-coupled-quantum-well (TCQW) structure is formed (as shown in Fig. 2) and a very large Stark shift can be attained. The nonlinear optical properties of the TCQW structures have been studied and a strong Stark tuning effect for the nonlinear optical susceptibilities has been observed experimentally. The band diagram and envelope wave functions of the TCQW without applied electric field are shown in Fig. 2. The basic TCQW structures are composed of three quantum wells separated by two barriers (about 16 Å) thin enough that considerable interaction occurs between electronic states in these wells. In this way, electrons in each well can interact strongly with each other to achieve a large Stark tuning effect. The TCQW structures now have three sub-band levels instead of two sub-band levels found in CQW structures. This extra sub-band level $E_2$ is due to the use of a middle quantum well in the TCQW.

The intersub-band Stark effect in the TCQW structures is studied theoretically in this paper. Results indicate that the TCQW structures exhibit very large Stark shifts of the $1 \rightarrow 3$ intersub-band transition. By using a $1 \rightarrow 3$ intersub-band Stark shift in the TCQW structure, a very large tunability far-infrared photodetector is presented. This photodetector can be used for the application in the 8–14 μm atmospheric window region. The operation of this device is based on the infrared absorption by electrons in the ground-state sub-band transited from $E_1$ of the TCQW to $E_3$. A very large variation of eigenenergy spacing $\Delta E_{31}$ between $E_3$ and $E_1$ under an applied electric field is achieved. Since the infrared radiation is absorbed through the intersub-band resonance absorption ($\hbar \omega = E_3 - E_1$), the detected infrared wavelength can be tuned by the $\Delta E_{31}$, which can be adjusted by the applied electric field. The characteristics of the tunability of the AlGaAs/GaAs TCQW structure is studied theoretically here. Based on the theoretical calculations, a tuning range from 7.9 to 15 μm is predicted by varying the applied electric field in the 60 to −60 kV/cm range.

Although the AlGaAs/GaAs TCQW does give a large Stark tuning effect, still this AlGaAs/GaAs TCQW possesses rather small $1 \rightarrow 3$ transition dipole matrix element $M_{31}$ and a low absorption coefficient. Instead of the TCQW with a uniform well depth, a GaInAs/AlGaAs/GaAs two-depth TCQW is proposed to increase the absorption coefficient without sacrificing the tunability. The two-depth TCQW structure (Fig. 3) does exhibit a very large and nearly linear voltage-controlled intersub-band Stark shift while maintaining a large transition dipole matrix element. The band diagram and envelope wave functions of the two-depth TCQW without applied electric field are shown in Fig. 3. The two-depth TCQW structure consists of three quantum wells with different depths separated by two thin barriers. The depth of each well is 52, 21, and 52 Å, respectively. The barrier height is 250 meV and the barrier width is 30 Å.
quantum well can be individually controlled by the composition of the quantum well. In this study, a Ga\textsubscript{1-x}In\textsubscript{x}As layer is assigned as the deep quantum well, GaAs layers are used as two shallow quantum wells, and Al\textsubscript{x}Ga\textsubscript{1-x}As layers are used as barriers. The two-depth TCQW structure with this extra design parameter of the well-depth difference $\Delta U$ will render much more flexibility in customizing the sub-band eigenenergy levels and the envelope wave functions in the well which may be adjusted to obtain a higher transition dipole matrix element $M_{31}$. By taking advantage of both a large Stark shift and a higher absorption coefficient associated with the 1$\to$3 intersub-band transition of a two-depth TCQW, a sensitive voltage-tunable far-infrared photodetector with very large tunability is proposed in this article. The tuning range of this two-depth TCQW is from 7.4 to 14 $\mu$m as the applied electric field varies from 60 to $-60 \text{ kV/cm}$. In order to supply electrons to the ground-state sub-band, the well must be doped with an $N$-type dopant. In this study, only the wider left-hand-side well of the TCQW is assumed to be doped with silicon (the doping concentration is about $5\times10^{17} \text{ cm}^{-3}$). Under the influence of the ionization donor density, sub-band 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 numerical integration. The energy-dependent effective mass due to energy-band nonparabolicity and the effect of the exchange interaction on the ground-state sub-band are also taken into account in this paper. These analyses are then employed to determine the energy-band nonparabolicity induced lowering of the sub-band eigenenergies and the exchange-energy-induced shift in the resonance absorption peaks of the TCQW infrared photodetectors.

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

II. THEORY AND FORMALISM

In this section, a self-consistent method to evaluate the envelope wave functions and the potential profile is described for TCQW structures under the influence of an applied electric field and ionized donors. 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 bound-state eigenenergies of the one-dimensional finite potential well can be found by solving the time-independent Schrödinger equation

$$H\Psi_n(z) = \left( -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial z^2} + U(z) \right) \Psi_n(z) = E_n \Psi_n(z),$$

where $U(z) = -qV(z)$ represents the electronic potential-energy variation, $q$ the magnitude of electronic charge, $m^*$ the effective mass, $\hbar$ the reduced Planck's constant, and $E_n$ and $\Psi_n$, respectively, the energy eigenvalue and the envelope wave function of the $n$th eigenstate. At the heterointerface (such as Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs), the envelope 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

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

where $N_D(z)$ is the ionized donor concentration and $n(z)$ is the electron density. To solve the Schrödinger equation and 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. Poisson’s equation was then solved by the numerical integration to find the new potential profile for the known 2DEG profile from the Schrödinger equation. This process is repeated till the convergence criterion $|V_{i+1}(z) - V_i(z)/V_{i+1}| < \delta$ is reached, where $V_i(z)$ is the trial potential profile, $V_{i+1}(z)$ the resulting potential profile, and $\delta$ a small number.

The energy-dependent effective mass due to energy-band nonparabolicity has been taken into account in the article. This causes a lowering of sub-band energies of the higher-excited-state sub-band and the lowering effect becomes substantial for the second-excited-state sub-band. The exchange interaction between electrons in the ground-state sub-band is also considered here. Since the exchange interaction lowers the ground-state sub-band, it results in a blue shift of absorption peaks and the corresponding detector response peaks to shorter wavelengths. For a more detailed derivation, most materials can be found in Refs. 7 and 21.

III. RESULTS AND DISCUSSIONS

The mathematical method to find the sub-band eigenenergies and envelope wave functions of the TCQW structures with applied electric field has been developed in Sec. II. Based on these calculations, the Stark tuning effect of the TCQW structures and characteristics of the voltage-tunable infrared photodetector are discussed 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 $5\times10^{17} \text{ cm}^{-3}$, $T = 77 \text{ K}$, and the thickness of these two barriers is assumed to be 16 Å. The conduction-band-gap discontinuity and effective mass for the GaInAs/AlGaAs/GaAs material system used here are adopted from Ref. 25.

A. Stark tuning effect in the AlGaAs/GaAs TCQW system

The band diagram and envelope wave functions of an AlGaAs/GaAs TCQW structure without applied electric field are shown in Fig. 2. In order to have large Stark shifts, a middle quantum well is used to replace the middle barrier of the CQW. This middle quantum well will introduce an additional sub-band level $E_2$. Thus the TCQW will have three sub-band levels in the well instead of two sub-bands used in the CQW system. As shown in Fig. 2, the envelope wave function of the ground-state sub-band $E_1$ is mainly located in the wide left-hand-side well, that of the first-excited-state
sub-band $E_2$ is mainly located in the middle quantum well, and that of the second-excited-state $E_3$ is mainly located in the narrow right-hand-side well. Since the ground-state-sub-band and the second-excited-state-sub-band electrons reside in the opposite side of the TCQW, a very large Stark shift can be expected due to large potential drops between these two wells. The relation of the calculated eigenenergy spacing $\Delta E_{31}$ as a function of the applied electric field is shown in Fig. 4. The positive direction of the applied electric field is defined as from left to right (i.e., positive z direction). As expected, a large variation of $\Delta E_{31}$ does arise due to the applied electric field. It is evident that $\Delta E_{31}$ in this TCQW 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 sub-band spacing $\Delta E_{21}$ can be tuned in a broader range by the applied electric field.

The field-induced Stark shift in the eigenenergy spacing of $\Delta E_{31}$ is similar to the situation of the CQW structures. By assuming that the ground-state-sub-band electrons are located at the center of the left-hand-side well and the second-excited-state-sub-band electrons at the center of the right-hand-side well, the Stark shift in $\Delta E_{31}$ can be approximated as the potential drop between the centers of these two wells. The potential-energy drop between the centers of the wide left-hand-side well and that of the right-hand-side well is about 64 meV for the applied electric field of 60 kV/cm. The amount of shift of calculated $\Delta E_{31}$ is about 44.3 meV as the applied electric field varied from 0 to 60 kV/cm. Since the envelope wave function of the second-excited-state sub-band tends to lean toward the left-hand-side well, i.e., the lower potential-energy side (as shown in Fig. 5), under the applied electric field, the use of the potential-energy drop between the centers of these two wells will overestimate the true shift of $\Delta E_{31}$. If a negative electric field is applied to the TCQW, the envelope wave function of the ground-state sub-band will move toward the middle quantum well, i.e., the lower potential-energy side (as shown in Fig. 6), resulting in a great reduction of the magnitude of the red shift. Since $\Delta E_{21}$ is related to the separation between the center of the left-hand-side well and the middle quantum well, a smaller Stark shift for $\Delta E_{21}$ as compared to $\Delta E_{31}$ is expected. The amount of shift for $\Delta E_{21}$ is about 32.7 meV as the applied electric field varied from 0 to 60 kV/cm. As expected, the variation of $\Delta E_{31}$ under the applied electric field is larger than that of $\Delta E_{21}$. By using a 1→3 intersub-band Stark shift in the TCQW structures, tunable far-infrared photodetectors with very large tunability can be fabricated. Moreover, to have a large 1→3 Stark shift, the dimensions of these three wells shall be chosen carefully to maintain the envelope wave function of the ground-state sub-band located in the left-hand-side well and that of the second-excited-state sub-band located in the right-hand-side well.

### B. Absorption coefficient

The linear intersub-band optical-absorption coefficient within the conduction band of the quantum well can be expressed as

\[
\alpha(E) = \frac{2 \pi e^2}{m^* h} \frac{1}{E} \left| \frac{\partial E}{\partial z} \right|
\]

This expression relates the absorption coefficient $\alpha(E)$ to the change in energy $\Delta E$ with respect to the applied electric field $E$. The term $\frac{\partial E}{\partial z}$ represents the change in energy with respect to the position $z$, which is related to the potential drop between the wells.

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[FIG. 4. Relation of the calculated eigenenergy spacings $\Delta E_{31}$ and $\Delta E_{21}$ as a function of the applied electric field for the AlGaAs/GaAs TCQW structure.]

[FIG. 5. Electronic potential-energy profile $U(z)$ for the AlGaAs/GaAs TCQW structure under the applied electric field of 60 kV/cm.]

[FIG. 6. Electronic potential-energy profile $U(z)$ for the AlGaAs/GaAs TCQW structure under the applied electric field of −60 kV/cm.]
FIG. 7. Calculated 1→3 absorption coefficient as a function of the infrared photowavelength under various applied electric fields for the AlGaAs/GaAs TCQW structure.

\[
\alpha(\omega) = \omega \sqrt{\mu_0 \varepsilon} \sum_{m,n=1}^{3} \left| M_{mn} \right|^2 \times \ln \left( \frac{1 + \exp \left[ (E_F - E_n)/k_B T \right]}{1 + \exp \left[ (E_F - E_m)/k_B T \right]} \right) \times \frac{\hbar/\tau}{(E_m - E_n - \hbar \omega)^2 + (\hbar/\tau)^2},
\]

where \( \mu_0 \) is the permeability in vacuum, \( \varepsilon \) the dielectric constant, \( w \) the total quantum-well width, \( \tau \) the dephasing time (assumed to be 0.14 ps), \( E_F \) the Fermi level of the system, \( k_B \) the Boltzmann constant, and \( T \) the temperature. The dipole matrix element \( M_{mn} \) is given by

\[
M_{mn} = \int_{-w/2}^{w/2} \Psi_m^*(z) z | \Psi_n(z) | dz.
\]

It can easily be seen that the resonance absorption occurs at \( \hbar \omega = E_m - E_n \). Since \( E_3 - E_1 \) increases or decreases with an applied positive or negative electric field for the TCQWs, the absorption resonance can be easily tuned by the external electric field for the TCQW structures.

The absorption coefficient for the AlGaAs/GaAs TCQW structure is evaluated by using Eq. (3). The resulting relation between the absorption coefficient and the photon wavelength under various applied electric fields is shown in Fig. 7. It can be seen that this structure does give a very good tunability. The tuning range is from 7.9 to 15 \( \mu m \) under an applied electric field in the 60 to -60 kV/cm range. However, this TCQW structure has a rather low absorption coefficient which hinders its application in tunable photodetectors with high responsivity. It is evident from Fig. 8 that this low absorption coefficient is due to the low transition dipole matrix element \( M_{31} \). Note that the 1→3 transition dipole matrix element decreased greatly under an applied electric field of -40 kV/cm.

C. Voltage-tunable far-infrared photodetector

The 1→3 transition is forbidden in any symmetric quantum-well structures. Thus a large dipole matrix element \( M_{31} \) can be achieved by properly engineering the asymmetry of the TCQW. By a very careful choice of TCQW structure parameters, we report a GaInAs/AlGaAs/GaAs two-depth TCQW structure which exhibits a very large and near-linear voltage-controlled intersub-band Stark shift while maintaining a larger absorption coefficient throughout the tuning range (shown in Fig. 8). The band diagram and envelope wave functions of a two-depth TCQW without applied electric field are shown in Fig. 3. The relation of the sub-band eigenenergies and the eigenenergy difference \( \Delta E_{31} \) as a function of the applied electric field is shown in Fig. 8. As expected, a large field-induced shift of \( \Delta E_{31} \) is observed. The amount of shift is about 78 meV as the applied electric field varied from -60 to 60 kV/cm. In addition, if the applied electric field is raised further, the envelope wave function of

FIG. 8. The comparison of the transition dipole matrix element \( M_{31} \) as a function of the applied electric field between the AlGaAs/GaAs TCQW structure (lower line) and GaInAs/AlGaAs/GaAs two-depth TCQW structure (upper line).

FIG. 9. Resonant absorption energy \( \Delta E_{31} \) and the sub-band energies as a function of the applied electric field for the GaInAs/AlGaAs/GaAs two-depth TCQW structure.

TCQW structure under an applied electric field of 70 kV/cm. Note that both the envelope wave functions of the ground-state sub-band and that of the second-excited-state sub-band are located in the left-hand-side well.

The two-step TCQW will effectively reduce to a single-quantum well. Thus the sub-band spacing $\Delta E_{31}$ cannot be tuned very much and the $\Delta E_{31}$ line in Fig. 9 varies slowly in the 70–80 kV/cm electric-field range as expected. The peak absorption wavelength versus the applied electric field for the two-depth TCQW is plotted in Fig. 11. It is clear that this TCQW structure does have a larger absorption coefficient and still remains a very good tunability. The tuning range from 7.4 to 14 $\mu$m can be achieved with an applied electric field in the 60 to −60 kV/cm range.

IV. CONCLUSIONS

The quantum-confined Stark effect in the TCQW structures has been studied theoretically. These TCQW structures are demonstrated to have a very large Stark effect and can be used to fabricate tunable photodetectors with very large tunabilities. The tunability has been estimated by the self-consistent method, and the absorption coefficient of the TCQW photodetectors has also been studied. A GaInAs/AlGaAs/GaAs two-depth TCQW tunable photodetector with tuning ranges from 7.4 to 14 $\mu$m has been proposed. This photodetector is ideal for device applications in the 8–14 $\mu$m atmospheric spectral window region. By using a larger band offset material system, such as GaInAs/AlInAs grown on an InP substrate, a tunable photodetector for applications in the 3–5 $\mu$m atmospheric spectral window region can also be designed. Furthermore, the application of this enhanced Stark effect of the TCQWs is not limited to tunable photodetectors. For example, the modulator can also be a good area for possible application of this very large Stark effect.

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