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ADVETISEMENT
The enhanced Stark effects of coupled quantum wells and their application to tunable IR photodetectors

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A tunable asymmetric coupled quantum well far-infrared photodetector is proposed in this paper. The basic asymmetric coupled quantum wells are composed of two quantum wells separated by a thin barrier. In this way, the electron in each well interacts strongly with other electrons to achieve a large Stark tuning effect. The eigenenergies and the wave functions of the quantum-well structures are solved by the self-consistent method, and the effect of the exchange interaction on the ground-state subband has also been taken into account. The absorption coefficient is evaluated by the density-of-states formalism. Based on theoretical calculations, tuning ranges from 8.2 to 11.3 μm and 7.8 to 10.5 μm are predicted for the proposed asymmetric coupled-quantum-well structure and high-low coupled-quantum-well structure, respectively. This tuning capability is achieved by varying the applied electric field in the 20–90-kV/cm range.

I. INTRODUCTION

Over the last several years, because of the maturity of GaAs growth and processing technologies such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) etc., many new AlGaAs/GaAs quantum-well photodetectors based on the intersubband absorption have been proposed to replace the conventional HgCdTe photodetector. Up to now, long-wavelength infrared absorption between the ground state and the first excited state of modulation doped AlGaAs/GaAs quantum-well photodetectors has been observed, and novel infrared detectors using the doped single-quantum-well superlattice have been fabricated. These GaAs quantum-well detectors have a number of advantages such as high speed, narrow bandwidth, strong infrared intersubband absorption, a long mean free path of the photogenerated hot electrons, higher responsivity, higher detectivity \( D^* \), and lower dark current by increasing the thickness of the AlGaAs barrier. In order to increase the net absorption for possible detector applications, these devices were fabricated as a multipass waveguide by polishing a 45° angle on both edges of the substrate or by using chemically etched diffraction gratings. 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 λ=8–12 μm atmospheric window spectral region. In spite of the great advantages mentioned above, there is no evidence of the Stark shift for all of these single quantum well detectors.

Based on the enhanced Stark effect of the AlGaAs/GaAs asymmetric coupled-quantum-well structure, a tunable far-infrared photodetector is proposed in this paper. The asymmetric coupled-quantum-well structure consisted of a pair of quantum wells separated by a barrier (about 30 Å) 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. Like those single quantum well detectors, the coupled quantum well structures were designed to have only two confined states, the ground state \( E_1 \) and the first excited state \( E_2 \). The infrared radiation is absorbed via the intersubband resonance absorption (for the incident photon energy \( h\omega = E_2 - E_1 \)), and the photoexcited electrons can tunnel out of the well to produce photoelectrons. The characteristics of the tunability of these AlGaAs/GaAs coupled quantum wells has been studied in this paper. The theoretical calculations show that both the symmetric coupled-quantum-well and the asymmetric coupled-quantum-well structures do give good tunability. However, the former cannot be used for fabricating a λ=8–12 μm photodetector because of the insufficiency resonant absorption energy and the lower absorption coefficient. In contrast, the asymmetric coupled quantum well photodetectors do give a large enough eigenenergy difference \( \Delta E = E_2 - E_1 \) to detect λ=8–12 μm atmospheric window spectral region. Based on theoretical calculations, tuning ranges from 8.2 to 11.3 μm and 7.8 to 10.5 μm are predicted for the asymmetric coupled-quantum-well structure.

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and for the high-low coupled quantum well structure, respectively. This tuning capability is achieved by the applied electric field in the 20–90-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 well of the asymmetric coupled quantum wells are 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, a self-consistent method to solve the one-dimensional Schrödinger equation and Poisson’s equation is used in this paper. In the presence of a static electric field, although there are no bound states in the finite depth quantum well, there still exist some quasi-bound states in the well. Here, the staircase approximation of the transfer-matrix formalism$^{13}$ is used to calculate the wave function of the quasi-bound state of the coupled quantum-well system under the external electric field. The only assumption needed is that the wave function goes to zero at a position far away from the quantum well. As for the electronic potential energy profile of the coupled quantum wells, Poisson’s equation was solved by numerical integration method to give this electronic potential energy profile. The effect of the exchange interaction of electrons in the ground-state subband of the coupled quantum wells is also taken into account in this paper. This analysis is then employed to determine the exchange-energy-induced shift in the resonance absorption peaks of the coupled quantum-well infrared detectors.

II. THEORY AND FORMALISM

In this section, a self-consistent method to evaluate the wave function and the potential profile is described for coupled-quantum-well structures under the influence of an applied electric field and ionization donor density. 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 coupled quantum well 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 coupled-quantum-well system can be divided into three different categories: symmetric coupled quantum wells (Fig. 1), asymmetric coupled quantum wells (Fig. 2), and high-low coupled quantum wells (Fig. 3). The bound-state eigenenergies of the one-dimensional finite potential well can be found by solving the time-independent Schrödinger equation:

$$\hat{H}\psi = \left(-\frac{\hbar^2}{2m^*} \frac{d^2}{dz^2} + U(z)\right)\psi = E\psi, \quad (1)$$

where $U(z) = -qV(z)$ represents the electronic potential energy variation, $m^*$ is the effective mass of charge particle, and $\hbar = h/2\pi$, $h$ is Planck’s constant. $E$ and $\psi$, respectively, represent the energy eigenvalue and the eigenfunction of the bound state. At the Al$_x$Ga$_{1-x}$As/GaAs...
interface, the electronic wave function and its first derivative $\psi'(z)/m^*$ are assumed to satisfy the continuity condition. In the absence of the external electric field, a simple iterative technique to determine the bound-state energies and the wave functions has been introduced for coupled quantum wells. For the finite field problem, however, no corresponding analytical method has been developed. In this paper, the staircase approximation of the transfer-matrix formalism is used to evaluate the wavefunction and quasibound state of the coupled-quantum-well system under an external electric field. The only assumption needed is that the wave function goes to zero at position far away from the well ($z<0$ and $z>w$ as shown in Fig. 4). The electronic potential energy is assumed to be constant beyond $z=L$. Thus the wave function can be expressed as

$$\psi(z) = \begin{cases} A^+ \exp(k_{0z}z), & z<0 \\ B^- \exp(-k_{0z}z), & z>L \end{cases}$$

where $k_{0z}^2 = 2m^*(U_b-E)/\hbar^2$ and $k_{1z}^2 = 2m^*(U_b+qEL-E)/\hbar^2$ define wave vectors in the respective regions, $U_b$ is the barrier height, and $\hbar$ is the applied electric field. By using the transfer-matrix technique, $A^+$ and $B^-$ are related by the following equation:

$$S(0,L) = \begin{pmatrix} 0 & \exp(-k_{1z}L) \\ -k_{1z} \exp(-k_{1z}L) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} A^+ \\ B^- \end{pmatrix}.$$  \hspace{1cm} (3)

To apply this method, the coupled quantum well is divided into many thin sublayers and the electronic potential energy is assumed to be constant in each thin sublayer. The combined transfer matrix $S(0,L)$ is then the product of the transfer matrices of all sublayers. The coefficients $A^+$ and $B^-$ are a function of the energy parameter $E$. If we set $A^+ = 1$, the eigenvalues $E$ can be determined by finding the roots of Eq. (3).

After all of the eigenenergies and wave functions in the coupled quantum wells have been found, the two-dimensional electron density $n_j$ associated with the $j$th subband could be expressed as follows:

$$n_j = \frac{m^*k_{0z}^2}{\pi \hbar^2} \ln \left[ 1 + \exp \left( \frac{q(E_j-E)}{k_{0z}^2} \right) \right],$$

then the total 2D electron density would simply be the summation of $n_j$ associated with all subbands in the coupled quantum well:

$$N_{2D} = \sum_{j=1}^{2} n_j,$$

where 2D EG denotes the two-dimensional electron gas. The electrostatic potential $V(z)$ in the conduction band is determined by Poisson’s equation:

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

where $q$ is the charge of electron charge magnitude, $\epsilon$ is the dielectric constant, and $N^+(z)$ is the ionized donor concentration. The electron density profile $n_j(z)$ for the $j$th subband is just the electron concentration in the $j$th subband $n_j$ multiplied by $|\psi_j(z)|^2$, the probability of finding electron at $z$. The electron density $n(z)$ would simply be the summation of $n_j(z)$ associated with all subbands in the quantum well:

$$n(z) = \sum_{j=1}^{2} n_j |\psi_j(z)|^2.$$  \hspace{1cm} (7)

To solve the Schrödinger equation and Poisson’s equation self-consistently, an initial potential profile is first estimated. The Schrödinger equation was solved to find the eigenenergies and wave functions for the given potential profile. Poisson’s equation was then solved to find the new potential profile for the known 2D EG profile from the Schrödinger equation. This process is repeated until the convergence criterion $|V_{i+1}(z) - V_i(z)|/|V_i(z)| < \delta$ is reached, where $V_i(z)$ is the initial potential profile, $V_{i+1}(z)$ is the new potential profile, and $\delta$ is a small number.

Since there are many electrons in the ground-state subband, the exchange interaction between these electrons is considered here. The general expression for the ground-state intrasubband exchange interaction energy is given by[16-18]

$$E_{\text{ex}}(k) = -\frac{e^2}{2\sigma} \int_0^{kF} \frac{dk'}{(2\pi)^2} \int dz \int dz' \frac{e^{-|k-k'||z-z'|}}{|k-k'|} \left| \psi_1(z') \right|^2 \left| \psi_1(z) \right|^2,$$

where $k_F = (2\pi\sigma)^{1/2}$ is the radius of the two-dimensional electron gas associated with the ground-state subband, $\sigma$ is the electron sheet density, for example, $\sigma = n_d Z$ for a quantum well uniformly doped with a donor concentration $n_d$, $\psi_1$ is the ground-state wave function, $e$ is the dielectric constant of GaAs, and $k$ and $k'$ are two-dimensional electron wave vectors. Since the exchange interaction lowers the ground-state subband, it results in a shift of absorption peaks and detector response peaks to shorter wavelengths. With a doping density of $5\times10^{17}$ cm$^{-3}$, the exchange effect gives an additional 5.7-meV shift in resonance energy. The
direct interband Coulomb interaction\textsuperscript{17} is repulsive and raises subband energies of the coupled quantum wells by about 0.5 meV, which is an order of magnitude smaller than the correction of the exchange interaction. Thus this correction due to the interband Coulomb interaction is neglected here. Since the electron density is not high enough in this structure, the correlation energy beyond the Hartree-Fock approximation should be very small and could also be neglected here.

Based on the density matrix formalism, the linear intersubband optical absorption coefficient within the conduction band of the GaAs quantum well can be expressed as\textsuperscript{19}

\[
\alpha(\omega) = \mu_0 \left( \frac{m^* K_b T}{\omega^2} \right) |M_{21}|^2 
\times \ln \left( \frac{1 + \exp \left( \frac{(E_F - E_{1})}{K_b T} \right)}{1 + \exp \left( \frac{(E_F - E_{2})}{K_b T} \right)} \right)
\times \frac{\hbar}{\tau} 
\times (E_{2} - E_{1} - \hbar \omega)^2 + (\hbar/\tau)^2, \tag{9}
\]

where \(\mu_0\) is the permeability in vacuum, \(\varepsilon\) is the dielectric constant of GaAs, \(w\) is the total quantum well width, \(\tau_1\) and \(\tau_2\) are the relaxation time constants for the ground state and first excited state, respectively. Here we assume that \(\tau_1 = \tau_2 = \tau\). The Fermi level \(E_F\) used in Eq. (9) can be obtained from Eq. (5). The dipole matrix element \(M_{21}\) is given by

\[
M_{21} = \int_{-w/2}^{w/2} \psi_2^*(z) \varepsilon z \psi_1(z) \, dz.
\]

The above result for the linear absorption coefficient can also be derived by using the Fermi golden rule.\textsuperscript{20} It can easily be seen that the resonance absorption occurs at \(\hbar \omega = E_2 - E_1\). Since \(E_2 - E_1\) increases with an applied electric field for the coupled quantum wells, the absorption resonance can be easily tuned by the external electric field for these coupled quantum wells.

III. RESULTS AND DISCUSSION

The mathematical method to find the eigenenergies and wave functions of the Schrödinger equation for various coupled-quantum-well structures with applied electric field have been developed in Sec. II. The theories for the absorption coefficient have also been studied. Based on these calculations, numerical results and discussions are presented in this section.

A. The Stark effect of symmetric coupled-quantum-well systems

The structure and wave functions of symmetric coupled quantum wells without applied electric field are shown in Fig. 1. The relation of the subband eigenenergies and the eigenenergies difference \(\Delta E\) between these two subbands as a function of the applied electric field is shown in Fig. 5. As expected, a large variation of \(\Delta E\) arises due to the applied electric field. Thus the symmetric coupled quantum wells do have a large Stark effect. The eigenenergies and the wave functions of the symmetric coupled quantum wells with an applied electric field (50 kV/cm) are shown in Fig. 4. By comparing the wave functions of Fig. 1 to those of Fig. 4, the advantage of the coupled effect of the symmetric coupled quantum wells becomes evident. This effect occurs as the electron density of the ground-state wave function and that of the first excited-state wave function tend to shift oppositely in the presence of an electric field. The electrons residing in these two states 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 \(\Delta E\). Thus coupled quantum wells do have very good tunability.

The absorption coefficient can be evaluated by using Eq. (9). The relation between the absorption coefficient and the applied electric field for the single quantum well with a well width of 50 Å and a well depth of 250 meV is shown in Fig. 6. The resonant absorption wavelength is insensitive to the applied electric field, as expected. It has virtually no tunability at all. In Fig. 7, the variation of the absorption coefficient as a function of the applied electric field for the symmetric coupled-quantum-well structure is
plotted. It is evident that this structure does give good tunability. Still, this symmetry structure has two drawbacks as a possible candidate for 8–12-μm infrared detectors. First, the ΔE cannot be stretched too far from zero by the electric field alone. Second, the absorption coefficient drops sharply at high electric fields due to the reduction of the overlap of electron wave functions. Thus this structure cannot be used for a λ=8–12 μm photodetector.

B. Asymmetric coupled-quantum-well systems

These two drawbacks of the symmetric coupled-quantum-well system are both related to the smallness of ΔE at zero field. This ΔE at zero field can be enlarged by the following two methods: (1) the use of a narrow well (asymmetric coupled wells) and (2) the use of a shallow well (high-low coupled quantum wells). Based on the quantum size effect, higher ΔE is expected for the asymmetric coupled quantum wells. In Fig. 8, the influence of the ratio of left well and right well width R_l to the eigenenergy difference ΔE under an applied electric field of 50 kV/cm is plotted. This curve can be divided into two regions: the rising region (1≤R_l<3) and the falling region (3≤R_l<9). The ΔE rises up to about 120 meV at R_l=3 and then falls back. As R_l is raised, the width of the right well becomes narrower than that of the left well. The ground-state energy of the right well will be raised due to the quantum size effect. Since this ground-state eigenenergy of the right well is roughly equal to the first excited-state eigenenergy of the whole coupled quantum wells, an increased of ΔE is expected. Thus the ΔE goes upward as R_l is raised. If R_l is raised further, the right well will be too narrow so that even the eigenenergy of the first excited state of the left well will be lower than the eigenenergy of the ground state of this narrow right well. Both the ground state and the first excited state fall in the left well as shown in Fig. 9. Thus, a coupled quantum well behaves like a single quantum well and the ΔE falls back, as expected for a single quantum well. By choosing the proper R_l value, ΔE of the asymmetric structure can be made much larger than that of the symmetric structure under the same applied electric field.

In Fig. 10, the relation between the absorption coefficient and the applied electric field is plotted for the asymmetric coupled-quantum-well structure. It can be seen that this structure does have large enough ΔE and still gives...
very good tunability. The tuning range is from 8.2 to 11.3 μm. This tuning capability is achieved with an applied electric field in the 90-20 kV/cm range. By comparison with Fig. 7, the absorption coefficient of this structure is much higher than that of the symmetric coupled quantum wells. In the absence of an electric field, the wave function of the first excited state is located in the right well and that of the ground state in the left well as shown in Fig. 2. Once an electric field is applied to the coupled quantum wells, the wave function of the first excited state tends to lean toward the higher potential energy and that of the ground state toward the lower potential energy part. If the left-hand side of the coupled quantum well is raised, then the wave function of the first excited state will shift into the left well. In this way, a higher dipole matrix element is expected due to the enhancement of wave-function overlap. As a result, a higher absorption coefficient is expected for asymmetric coupled quantum wells.

C. High-low coupled-quantum-well structures

The peak absorption wavelength versus the applied electric field for the high-low coupled quantum well (as shown in Fig. 3) is plotted in Fig. 11. By introducing the additional difference of the quantum well depth, the energy of the first excited state can be pushed even higher. The \( \Delta E \) of this structure will be higher than that of the asymmetric structure under the same applied electric field. The structure can be designed to detect even shorter-wavelength infrared radiation. The spectral response of the proposed coupled high-low quantum well is from 7.8 to 10.5 μm as the electric field varies from 20 to 90 kV/cm.

There are two sources that contribute to the intersubband eigenenergy separation \( \Delta E \), the initial zero-field separation \( \Delta E_0 \) and the field-induced Stark separation \( \Delta E'_S \). \( \Delta E_0 \) can be approximated as the difference between the ground-state eigenenergies of two noninteracting wells. By assuming that the ground-state electrons are located at the center of the wide well and the first excited-state electrons at the center of the narrow well, \( \Delta E_0 \) can be approximated as the product of the electric field and the distance between the centers of these two coupled wells. For the desired variation of \( \Delta E \), the corresponding structure of the coupled quantum wells can be designed from the approximate estimations of \( \Delta E_0 \) and \( \Delta E'_S \).

The above system cannot be used for the design of a detector for wavelengths shorter than 6 μm due to the limitation of the conduction-band offset. To design a tunable photodetector for long-distance fiber communications, a detecting wavelength around 3 μm is needed, and a larger conduction-band offset energy is required. This can be implemented by using a larger band offset material, such as InGaAs/InAlAs grown on an InP substrate.

IV. CONCLUSION

Conventional multi-quantum-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 coefficient of coupled-quantum-well photodetectors has been studied. An Al\(_{x}\)Ga\(_{1-x}\)As/GaAs asymmetric coupled-quantum-well photodetector and a high-low coupled-quantum-well tunable photodetector with tuning ranges from 8.2 to 11.3 μm and 7.8 to 10.5 μm, respectively, have been proposed. These photodetectors are ideal for the 8-12-μm atmospheric spectral window. By using a larger band offset material, such as InGaAs/InAlAs grown on an InP substrate, a tunable photodetector for the application of long-distance fiber communications can also be designed. Furthermore, the application of this enhanced Stark effect of the coupled quantum well is not limited to tunable photodetectors. For example, the modulator can be a good area for possible applications of this enhanced Stark effect.

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