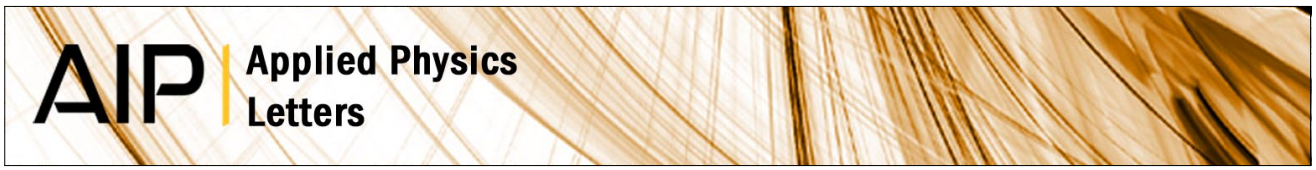

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Strong blueshift of the excitonic transition in the InGaAs/InP/InAsP antisymmetric coupled quantum wells

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A new strained InGaAs/InP/InAsP antisymmetric coupled-quantum-well (CQW) structure with significant enhancement of the blue and red Stark effects in the first heavy-hole-to-electron excitonic transition is proposed in this letter. The calculated amount of blueshift is about 48 meV as the applied electric field varied from 0 to 90 kV/cm and the red Stark shift of about 56 meV can be achieved with an applied electric field in the 0 to −90 kV/cm range. The results of the strong Stark effect in the antisymmetric CQW structure may have potential applications in sophisticated new electronic devices, such as optical switching devices and tunable lasers. © *1995 American Institute of Physics.*

Recently, the field dependence of optical properties in semiconductor quantum wells for application in optoelectronic devices have been studied intensively.[1–7] The most extensively studied and utilized subject is the quantum-confined Stark effect (OCSE).[1–7] As an external electric field is applied, the shape of the quantum-well potential deforms and the transition energies of the eigenstates change accordingly. The QCSE is generally referred to as a shift of the transition energies in a quantum well upon the application of an electric field. The Stark shifts have been observed both for the exciton absorption peak of the interband transition[2–4] and for the intersubband absorption[5] in quantum-well structures. This Stark effect has been applied in high-performance optoelectronic devices such as high speed modulators,[2] self-electro-optic-effect devices,[1] and wavelength-selective voltage-tunable photodetectors.[7]

From the device point of view, it is desirable to have a quantum-well structure with a large Stark shift under a low driving voltage. The Stark shift of a square quantum well has been studied and the resulting shift compared to the peak width is rather small for the practical device applications.[1,2] The coupled-quantum-well (CQW) structures, usually consisting of two quantum wells separated by a thin barrier, are proven to have a large Stark shift for both interband and intersubband transitions.[3,4] Very strong red Stark shifts of excitonic transitions in this quantum-well structure have been observed experimentally.[3,4] However, a large blue Stark shift of excitonic transitions is difficult to achieve for these kinds of conventional CQW structures.[6] Only a few quantum-well structures with large blue Stark shifts of the excitonic transition have been proposed.[8] In this letter, we report a new strained InGaAs/InP/InAsP antisymmetric CQW structure (Fig. 1) which exhibits both a large blue and red Stark shift of the first heavy-hole-to-electron ($E_{\mathrm{hh1}}\rightarrow E_{\mathrm{e1}}$) excitonic transition.

Strained InAsP/InP quantum-well structures have been fabricated recently and many high performance optoelectronic devices have also been made.[8–11] The optical and electronic response in these types of quantum wells can be tailored by varying the strain and the thickness of the pseudomorphic layer and even the substrate orientation.[9] Thus, many novel electronic and optoelectronic devices can be developed. The strained InAsP/InP material system is adopted in this study to realize an antisymmetric conduction-band (CB) and valence-band (VB) CQW profile. The schematic band diagram of an antisymmetric CQW is shown in Fig. 1. The antisymmetric CQW consists of a pair of 42 Å $In_{0.53}Ga_{0.47}As$ and $InAs_xP_{1-x}$ quantum wells separated by a 21 Å InP middle barrier surrounded by InP outer barrier. An arsenic mole fraction $x=0.4$ is used in this antisymmetric CQW potential profile (as shown in Fig. 1) which gives both large blue and red Stark shifts of the excitonic transition.

The calculation of the CB and VB eigenenergies is based on the effective mass approximation. The CB eigenenergies of the one-dimensional potential well can be found by solving the time-independent Schrödinger equation:

$$H_{\mathrm{e}}\psi_{\mathrm{e}}=\left(-\frac{\hbar^2}{2m_{\mathrm{e}}^*}\frac{\partial^2}{\partial z^2}+U_{\mathrm{e}}(z)+eFz\right)\psi_{\mathrm{e}}=\mathrm{E}_{\mathrm{e}}\psi_{\mathrm{e}}, \qquad (1)$$

where $U_{\mathrm{e}}(z)$ is the rectangular quantum-well potential for

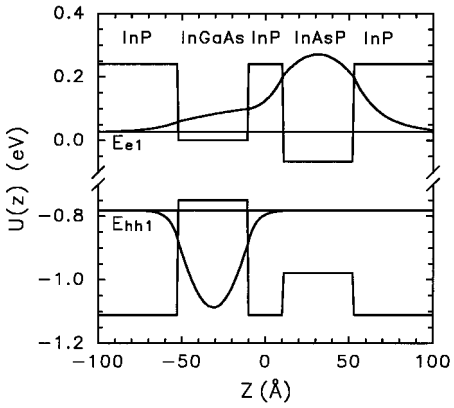

FIG. 1. Schematic band diagram of a strained InGaAs/InP/InAsP antisymmetric coupled quantum well. This quantum-well structure consists of a pair of 42 Å $In_{0.53}Ga_{0.47}As$ and strained $InAs_{0.4}P_{0.6}$ quantum wells, and are separated by a 21 Å InP barrier.

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electrons due to the CB discontinuity, m_e^* is the effective mass of electrons in the conduction band, F is the applied electric field, and $\hbar$ is the reduced Plank's constant. E_e and ψ_e represent the energy eigenvalue and eigenfunction of the electron in the conduction band. At the heterointerface, the electronic wave function and its first derivative ψ_e'/m_e^* are assumed to satisfy the continuity condition. In the presence of a static electric field, the staircase approximation of the transfer-matrix formalism is used to calculate the envelope wave functions of the quasibound state of the antisymmetric CQW system under the external electric field.[12] The only assumption needed is that the envelope wave functions go to zero at a position far away from the quantum well. The calculation of transition energies in this antisymmetric CQW system involves calculation of both VB CQW and CB CQW eigenenergies. The calculation of the CB CQW eigenenergies proceeds as described above. However, to ensure computational simplicity, several assumptions have been made in modeling the valence band. The heavy and light holes were treated separately and band mixing effects between the heavy and light holes were not included. With these assumptions, the valence band can be solved computationally as if it were a CB quantum well under the opposite sign of field (incorporating appropriate changes in the values of the effective mass and depth of the quantum-well structure).

The effect of the strain on the energy gap of the InAsP layers is considered by using standard elasticity theory.[10] In an approximation of the elastic deformation, a biaxial compressive strain is present in the InAsP layer when it is grown on the InP substrate.[9] The strain is assumed only in the InAsP layer, because the thickness of the InP substrate is far larger than that of the InAsP layer[9] and a lattice matched InGaAs layer is used as another well of the antisymmetric CQW. Due to the strain effect, the change of the energy gap E_g between the bottom of the conduction band and the degenerate top of the valence bands is[10]

$$\Delta E_{hh}=\left(2\mathbf{a}\,\frac{C_{11}-C_{12}}{C_{11}}-\mathbf{b}\,\frac{C_{11}+2C_{12}}{C_{11}}\right)\epsilon_0 \tag{2}$$

for the heavy hole and

$$\Delta E_{lh}=\left(2\mathbf{a}\,\frac{C_{11}-C_{12}}{C_{11}}+\mathbf{b}\,\frac{C_{11}+2C_{12}}{C_{11}}\right)\epsilon_0 \tag{3}$$

for the light hole, where $\epsilon_0\equiv(a_{InP}-a_{InAsP})/a_{InAsP}$ is the biaxial strain, a_{InP} and a_{InAsP} are respective lattice constants of the unstrained InAsP and InP, **a** is the hydrostatic deformation potential, **b** is the shear deformation potential, and $C_{11}$and C_{12} are the elastic stiffness constants. The physical parameters used in this calculation are listed in Table I. By assuming that the Vegard's law holds, the parameters for the InAsP are estimated by linearly interpolating from the values of both end binary compounds.[9] The theoretical variation of the exciton binding energy as a function of the electric field has also been calculated by the variational method.[1] Very small 1.4 meV field-induced changes of the exciton binding energy as compared to the 114 meV field-induced changes of the $E_{hh1}\rightarrow E_{e1}$ excitonic transition energy in the -90 to 90 kV/cm range are found for this antisymmetric CQW. Thus, a constant exciton binding energy of 8.5 meV[9] at zero field is adopted in this letter. The energy gap of the unstrained $InAs_xP_{1-x}$ compound was chosen to be $E_g(x)=1.351-1.315x+0.32x^2$ (eV) at 300 K.[9] The VB offset ratio $Q_v(\equiv\Delta E_v/\Delta E_g)$ between the InP barrier layer and the InAsP well layer was assumed to be 0.3.[9] As for the $In_{0.53}Ga_{0.47}As$ layer, the E_g is the assumed to be 0.75 eV at 300 K and Q_v is assumed to be 0.6.[13] The antisymmetric CQW is assumed to be grown on the (100) InP substrate.

TABLE I. Physical parameters used in the present calculation.[a]

	InP	InAs	GaAs
Lattice constant	5.8687	6.0584	
$C_{11}(10^{11}\text{dyn/cm}^2)$	10.11	8.33	
$C_{12}(10^{11}\text{dyn/cm}^2)$	5.61	4.526	
a (eV)	−7.4	−6.9	
b (eV)	−1.7	−1.7	
$m_e^*(m_0)$	0.076	0.0231	0.067[b]
$m_{hh}^*(m_0)$	0.472	0.34	0.49[b]

[a]H. Q. Hou and C. W. Tu, J. Appl. Phys. **75**, 4673 (1994).
[b]V. Swaminathan and A. T. Macrander, *Materials Aspects of GaAs and InP Based Structures* (Prentice Hall, Englewood Cliffs, NJ, 1991).

The calculated Stark shift of excitonic energy as a function of the applied electric field for the first heavy hole $[\delta E_{hh1}=E_{hh1}(0)-E_{hh1}(F)]$ and electron $[\delta E_{el}=E_{el}(F)-E_{el}(0)]$ eigenenergy levels in the antisymmetric CQW is shown in Fig. 2. The total amount of energy shift for the $E_{hh1}\rightarrow E_{e1}$ excitonic transition is the sum of the δE_{hh1} and δE_{e1}. The positive direction of the applied electric field is defined from left to right (i.e., positive z direction). A large variation of the E_{hh1} and E_{e1} is observed under the applied electric field. It is evident that the E_{hh1} and E_{e1} for this antisymmetric CQW structure can either be red or blue Stark shifted depending on the direction of the applied electric field. The blueshifts occur when the applied electric field is positive. The redshifts occur when the applied electric field is negative. Notice that, as an electric field is applied to the antisymmetric CQW structure, the QCSE energy shifts,

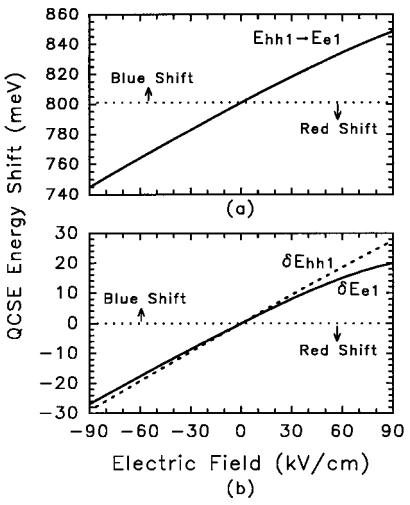

FIG. 2. (a) Calculated $E_{hh1}\rightarrow E_{e1}$ excitonic transition energy and (b) QCSE energy shifts, δE_{e1} (solid line) and δE_{hh1} (dashed line), as a function of the applied electric field.

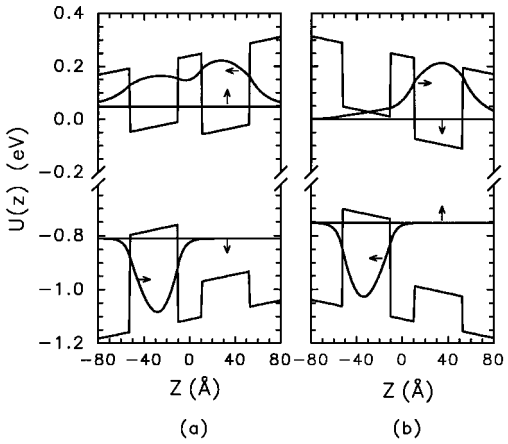

FIG. 3. Electronic potential energy profile for the antisymmetric CQW structure under the applied electric field of (a) 90 and (b) −90 kV/cm.

δE_{e1} and δE_{hh1}, are in the same direction and the corresponding Stark shift of the $E_{hh1} \rightarrow E_{e1}$ excitonic transition energy will be very large due to the summation of the δE_{e1} and δE_{hh1}. The calculated amount of blueshift is about 48 meV as the applied electric field varied from 0 to 90 kV/cm and the red Stark shift of about 56 meV can be achieved with an applied electric field in the 0 to −90 kV/cm range. This strong Stark effect in the antisymmetric CQW structure may have many potential applications in sophisticated new electronic devices, such as optical switching devices and tunable lasers.

The schematic band diagrams and envelope wave functions of the antisymmetric CQW under the applied electric field of 90 and −90 kV/cm are shown in Figs. 3(a) and 3(b), respectively. By inspecting the E_{e1} and envelope wave function of the conduction band (part of Figs. 1 and 3), it can be seen that E_{e1} shifts upward (δE_{e1} is positive) under the positive electric field [Fig. 3(a)] and downward (δE_{e1} is negative) under the negative electric field for this coupled high–low quantum-well structure. From Fig. 1, in the absence of the electric field, the envelope wave function of the E_{e1} is located at the center of the right-hand-side well (low potential-energy side). As a positive electric field is applied, the CB tilts and the potential of the left-hand-side well decreases. In this way, the envelope wave function of the E_{e1} tends to lean toward the shallow left-hand-side well and results in an increase of the energy of the E_{e1}(blue shift). On the other hand, if a negative electric field is applied, the E_{e1} envelope wave function is mainly confined in the deep right-hand-side well and results in an overall net reduction in the energy of the E_{e1} (redshift). As for the valence band, it should be noted that the deep well is located at the left-hand side and the shallow well at the right-hand side for this antisymmetric CQW structure. Since the E_{hh1} envelope wave function tends to move toward the higher potential energy side (i.e., the shallow right-hand-side well) under the positive electric field, similar arguments described above for the Stark shift of the eigenenergy E_{e1} can be applied directly to the eigenenergy E_{hh1}. As a result, both E_{e1} and E_{hh1} will have a blue Stark shift under positive field and a red Stark shift under negative field. In addition, for the conventional high-low CQW, the deep VB well is located at the right-hand side and the shallow VB well at the left-hand side. Thus, E_{e1} and E_{hh1} behave oppositely under the electric field. E_{e1} will shift upward (blueshift) while E_{hh1} will move upward (redshift) under the positive electric field. As a result, δE_{e1} is positive while δE_{hh1} is negative under the positive electric field. Thus, the possibility of achieving the blueshift is greatly reduced.

In conclusion, the antisymmetric CQW structure has been employed to greatly enhance the blue Stark shift of the $E_{hh1} \rightarrow E_{e1}$ excitonic transition. This antisymmetric CQW structure can lead to the development of novel optoelectronic devices based on the quantum confined Stark effect. Furthermore, the assumption of the InGaAs/InP/InAsP material system is not essential in this calculation; any quantum-well system that can be designed to form an antisymmetric quantum-well structure will give a large blue Stark shift.

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