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Large asymmetric Stark shift in $Ga_xIn_{1-x}As/InP/InAs_yP_{1-y}$ composite quantum wells

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Strong asymmetric Stark shift in excess of 115 meV of the lowest energy transition has been experimentally observed in composite $Ga_xIn_{1-x}As/InP/InAs_yP_{1-y}$ quantum-well system. In this structure, we can independently control the confinement of electrons and holes by controlling the strain. The photoexcited electrons and holes are confined in spatially separated regions without the application of an electric field. Due to the large asymmetry in the structure, we observed large blueshifts and redshifts of the absorption edge with an applied electric field. All our measurements agree with the calculations within the framework of the Bir–Pikus strain Hamiltonian. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1616664]

Asymmetric Stark shifts were found in structures with spatial separation of electrons and holes. In these types of structures the blueshifts and redshifts are determined by the direction of the applied electric field. In recent years, there has been a great deal of interest in structures with spatially separated electron–hole systems. They are especially used to realize a two-dimensional exciton condensate[1,2] and for exploring the blue shifting potentialities of the absorption edge.[3] Multi-quantum-well (MQW) structures based on quantum confined Stark effect (QCSE)[4] have been widely used in self-electro-optic effect devices (SEED).[5] In a conventional SEED, to assure the positive feedback, the existence of the sharp excitonic peak is essential. One drawback of this method is that it suffers from large residual absorption. SEEDs based on blueshift are less reliant on sharp excitonic peaks and offer significant improvements in terms of on/off ratio and insertion loss over the usual redshift devices.[6,7] To enhance the blue Stark shift, several theoretical and experimental proposals were made by different groups.[6–15] However, the largest blueshift was achieved in a ⟨111⟩ $In_{0.10}Ga_{0.90}As/GaAs$ MQW structure[15] and was limited to 22 meV at a field of 85 kV/cm. In that case, an electric field is applied opposite to the piezoelectric field, essentially compensating the pre-biased state of the structure. A built-in field, which is canceled by an external field, can also be achieved using either asymmetric coupled QWs[6,7] or graded gap QWs.[11]

In this letter, we present the experimental realization of a large asymmetric Stark shift of the ground state transition in $Ga_xIn_{1-x}As/InP/InAs_yP_{1-y}$ composite QW structures. In a strain balanced structure, the magnitude of the total Stark shift is 117 meV, of which 35 meV is blueshift. We can independently control the confinement of electrons and holes in this structure by careful strain engineering. This structure can confine electrons and holes in spatially separated regions without the application of an electric field. The highly asymmetric structure allows large tuning of the absorption edge to the blue or red side of the spectrum with an applied electric field.

The composite QW structures used in our experiments were grown by chemical-beam epitaxy on InP substrate, misoriented 0.5^0 towards the [111]B. The QW sequence was grown in the intrinsic region of an $n-i-p$ structure and consists of 4 nm thick $Ga_xIn_{1-x}As$ and $InAs_yP_{1-y}$ separated by a 1 nm thick InP barrier. We have studied two sets of samples; in one set, a reverse bias causes a redshift of the absorption edge and in the other it causes a blueshift. The blueshifting structures have an inverted QW sequence compared to the redshifting structures. The $InAs_yP_{1-y}$ layers with $y=0.42$ are always in compression with respect to the InP substrate, while the $Ga_xIn_{1-x}As$ layers were grown either lattice matched ($x=0.47$) or in tension ($x=0.67$; strain balanced sample). The resulting composite QW structures have a highly asymmetric potential profile due to the opposite weighting of their band offset parameters. At the $Ga_xIn_{1-x}As/InP$ interface the conduction band to valence band offset ratio is assumed to be 40:60[16] and at the $InAs_yP_{1-y}/InP$ interface it is taken to be 70:30.[17] Due to this reverse band offset ratio, an antisymmetric potential profile is formed with a shallow-deep conduction band and a deep-shallow valence band. The photocreated electrons are confined within the $InAs_yP_{1-y}$ well, while the holes are collected at the $Ga_xIn_{1-x}As$ part of the composite QW. This results in a zero-field separation of electrons and holes, and the situation is rather analogous to the effect of pre-biasing a QW with a static field. The QCSE will start out as a blueshift of the lowest electron–hole transition as the applied electric field reduces the separation of electrons and holes.

The spatial separation of electrons and holes in our structures allows us to study the blue Stark shift without making any electrical contact to the structures. The blue shift was studied using photoluminescence (PL) measurement. Since the QW sequence is in the intrinsic region of an $n-i-p$ structure, the spatially separated electron–hole sys-

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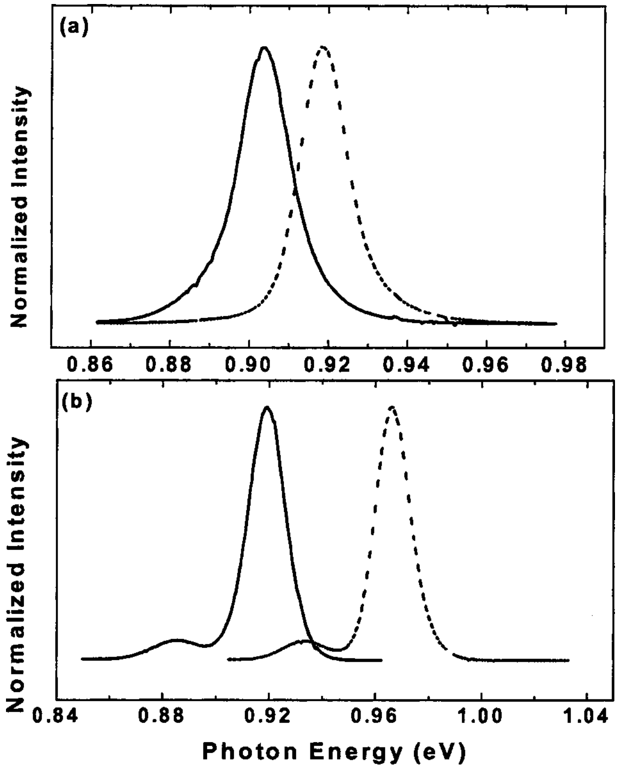

FIG. 1. Low-temperature PL spectra. Panel (a): $Ga_{0.47}In_{0.53}As$ lattice-matched samples; solid line for $InAs_{0.42}P_{0.58}/InP/Ga_{0.47}In_{0.53}As$ and the dashed line for $Ga_{0.47}In_{0.53}As/InP/InAs_{0.42}P_{0.58}$ sample. Panel (b): strain balanced samples; solid line for $InAs_{0.42}P_{0.58}/InP/Ga_{0.67}In_{0.33}As$ and dashed line for $Ga_{0.67}In_{0.33}As/InP/InAs_{0.42}P_{0.58}$ sample.

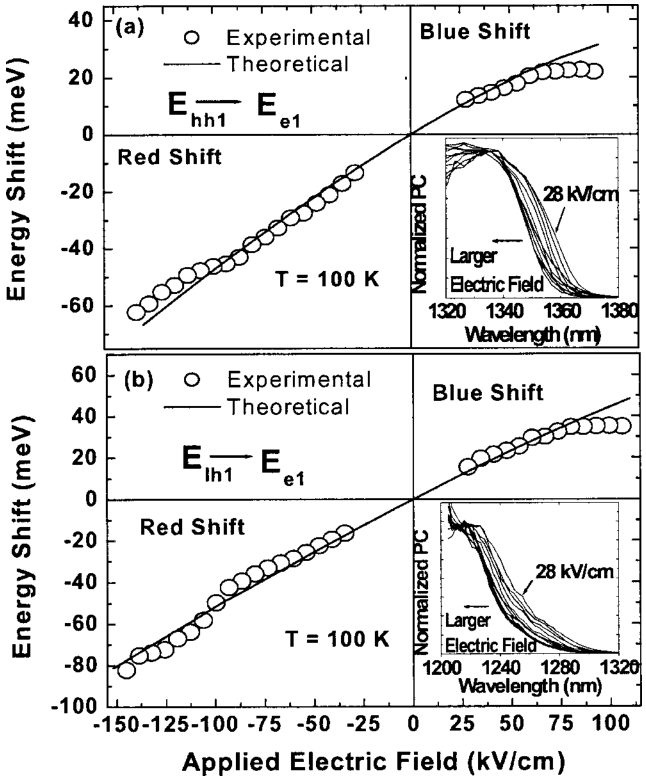

FIG. 2. Panel (a): Stark shift of the lowest hh–electron transition with respect to applied electric field in $Ga_{0.47}In_{0.53}As$ lattice-matched sample. Panel (b): Stark shift of the lowest lh–electron transition for the strain balanced sample. In both panels, the inset shows the PC spectra for the blue-shifting samples.

tem will experience a built-in electric field of 28 kV/cm. In one QW sequence this field pulls the electrons and holes to opposite sides of the structure resulting in a redshift of the ground state transition energy from the zero field value. In the inverted sequence the field pushes them close to each other resulting in a blue shift of the transition energy.

The PL measurements were done at 5 K in a He-flow cryostat. Samples were excited using a 532 nm second harmonic from an Nd:YAG laser and the estimated excitation density was 400 mW/cm^2. Figure 1(a) shows the intensity normalized PL spectra of the $Ga_{0.47}In_{0.53}As$ lattice-matched samples. The PL from these composite asymmetric QWs, even though via an indirect real space radiative transition, show strong PL bands with full width at half-maximum of less than 16 meV. For the $Ga_{0.47}In_{0.53}As$ lattice-matched samples, the shift between the two PL peaks is 15 meV. Figure 1(b) shows the intensity normalized PL spectra of the strain balanced samples. The shift between the PL peaks is 50 meV, which is increased by three times compared to the shift in the $Ga_{0.47}In_{0.53}As$ lattice-matched samples. The total shift includes both blueshift and redshift of the transition energy from the zero field value.

We used photocurrent (PC) spectroscopy to study the external electric-field-induced blueshift and redshift in these structures. Annealed Zn/Au and Ge/Au contacts were made to the *p*- and *n*-type layers, respectively. The PC measurements were done at 100 K in a He-flow cryostat. A tunable near infrared light is generated by mixing a 1.06-mkm Nd:YAG laser beam with a visible output from a synchronously pumped dye laser, which is used to excite the sample. The tuning range is from 1185 to 1670 nm.

Figure 2 shows the asymmetric Stark shifts observed in the $Ga_xIn_{1-x}As/InP/InAs_yP_{1-y}$ composite QW structures. The inset of Fig. 2(a) shows the PC spectra as a function of applied electric field for the $Ga_{0.47}In_{0.53}As/InP/InAs_{0.42}P_{0.58}$ QW structure. The right top side of Fig. 2(a) shows the blue Stark shift of the ground state heavy-hole(hh)–electron transition energy as a function of the applied electric field. The degree of polarization of the PL from the cleaved side of this sample demonstrates that the ground state is indeed hh in character. The observed blueshift was 22 meV for a maximum applied field of 93 kV/cm. In the strain balanced $Ga_{0.67}In_{0.33}As/InP/InAs_{0.42}P_{0.58}$ sample, the valence band ground state becomes light-hole (lh) in character. The inset of Fig. 2(b) shows the photocurrent spectra at different applied fields and the right top side of Fig. 2(b) shows the blue Stark shift of the lh electron transition. In this structure we realized a larger blueshift of 35 meV compared to the $Ga_{0.47}In_{0.53}As$ lattice-matched case.

We have also measured the red Stark shift in structures with the inverted layer sequence. At low fields we observed a linear Stark shift. This is a clear indication of the separate confinement of electrons and holes in real space. From the slope of the linear redshift, we calculated the electron–hole separation. The redshift is also shown in the bottom left of Figs. 2(a) and 2(b). For the $InAs_{0.42}P_{0.58}/InP/Ga_{0.47}In_{0.53}As$ sample the observed redshift is 62 meV and for the $InAs_{0.42}P_{0.58}/InP/Ga_{0.67}In_{0.33}As$ sample it is 82 meV. Thus,

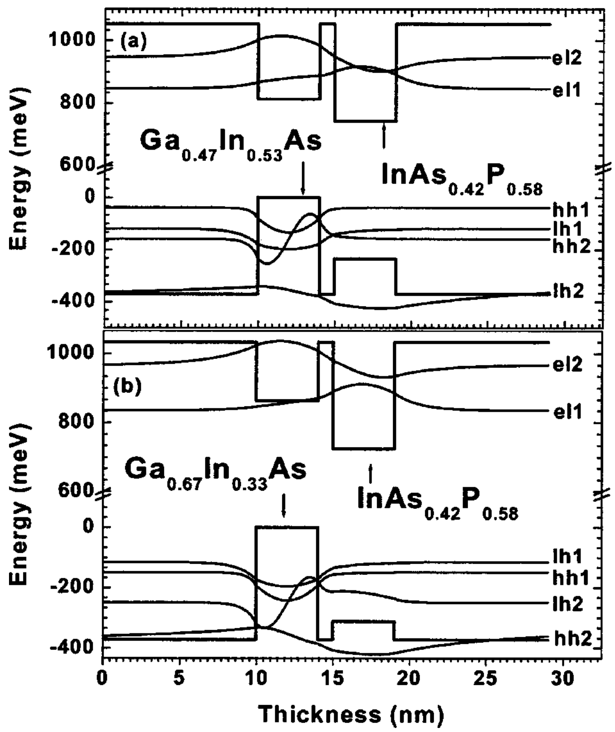

FIG. 3. Calculated potential profile and electron and hole wave functions for the blueshifting structures. The wave functions were calculated numerically for a temperature of 100 K. The redshifting structures have a similar profile, but with inverted QW sequence, compared to blueshifting structure. Panel (a): Potential profile and wave functions for $Ga_{0.47}In_{0.53}As/InP/InAs_{0.42}P_{0.58}$ sample at zero bias. Panel (b): Potential profile and wave functions for the strain balanced $Ga_{0.67}In_{0.33}As/InP/InAs_{0.42}P_{0.58}$ sample.

for the strain balanced sample, the total shift exceeds 115 meV. All the measurements are in agreement with our calculations done in the framework of Bir–Pikus strain Hamiltonian.

This large blueshift observed in the strain balanced structure is due to the better confinement of electrons in the structure. Figure 3(a) shows the calculated potential profile and electron and hole wave functions for the $Ga_{0.47}In_{0.53}As/InP/InAs_{0.42}P_{0.58}$ blueshifting structure at zero bias. Due to the reverse band offset ratio, a highly asymmetrical potential profile is formed. By inspecting the wave functions of both conduction band and valence band, it is evident that holes are located at the center of the $Ga_{0.47}In_{0.53}As$ well, while the electrons are almost at the center of the $InAs_{0.42}P_{0.58}$ well. There is a residual coupling in the conduction band, which reduces the electron–hole separation. The calculated nonzero dipole moment is 6.4×10^{-28} C m. The valence band ground state is hh in character.

By putting more tension on the $Ga_{0.67}In_{0.33}As$ side of the QW structure, we realized better confinement of electrons, and hence can increase the electron–hole separation. Figure 3(b) shows the calculated wave functions for the $Ga_{0.67}In_{0.33}As/InP/-InAs_{0.42}P_{0.58}$ blueshifting structure. The valence band ground state is lh in character. By putting more tension on the $Ga_{0.67}In_{0.33}As$ side of the composite QW, we can reduce the residual coupling in the conduction band. Here, compared to the $Ga_{0.47}In_{0.53}As$ lattice-matched case, the well depth difference for the conduction band is increased. This results in better confinement of photocreated electrons to the $InAs_{0.42}P_{0.58}$ well. The calculated nonzero dipole moment is 7.2×10^{-28} C m. Due to the increased initial charge separation, this structure shows large blue Stark shift of the lowest energy transition.

If we analyze the blueshifting part in Fig. 2, the experimentally observed values for the blueshift deviate from the theoretically calculated values at higher fields. For the strain balanced $Ga_{0.67}In_{0.33}As/InP/InAs_{0.42}P_{0.58}$ structure, the maximum value for the theoretically calculated blue shift is 70 meV at a field of 196 kV/cm, and for the $Ga_{0.47}In_{0.53}As$ lattice-matched case it is 42 meV at a field of 194 kV/cm. The theoretically calculated values for the maximum blueshift are higher than the experimentally observed ones. The experimentally observed blueshift shows saturation behavior. This saturation is caused by the electric-field-induced breakdown in the system, which is evident from a rapid increase in photocurrent at the beginning of the saturation behavior in both samples.

In conclusion, we have experimentally realized a large asymmetric Stark shift of 117 meV of the lowest energy transition in a strain balanced composite $Ga_xIn_{1-x}As/InP/InAs_yP_{1-y}$ quantum well system. By carefully adjusting the strain, we have realized optimal confinement characteristics for the electrons and holes individually. The spatial separation of electrons and holes in this system allowed us to measure the blue Stark shift without applying an external electric field.

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