Electroabsorption in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ asymmetric coupled quantum wells grown on InP substrates

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We report the results of photocurrent measurements on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ asymmetric coupled quantum wells lattice matched to InP substrates. We show that large shifts in excitonic absorptions with applied bias result from the resonant coupling of electron subbands. Results of our measurements agree well with calculations performed with use of a single-band envelope-function approximation that incorporates a scattering–phase-shift method for determining the quasibound electron- and hole-subband states of the coupled-well system in an electric field.

The rapid development of fiber-optic communications systems has stimulated a search for semiconductor electro-optic devices that operate in the 1.3- and 1.55-μm wavelength bands. Effects that have been thoroughly characterized[1–4] in $GaAs/Al_xGa_{1-x}As$ multiple quantum wells (MQW's) are now being investigated in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ (Refs. 5–7) and $In_{0.53}Ga_{0.47}As/InP$ (Refs. 8 and 9) quantum-well systems lattice matched to InP substrates. Many of the electro-optic devices being studied are based on an electric-field-induced shift in excitonic absorption peaks known as the quantum-confined Stark effect (QCSE).[1] However, the magnitude of the QCSE depends strongly on the well thicknesses (for isolated, rectangular wells) and can be very small for the relatively thin wells (3–8 nm) required for implementation in devices that operate at 1.3 and 1.55 μm. The development of effective quantum-well modulators for these wavelengths will depend on identifying new electroabsorption mechanisms that are not subject to this limitation.

In this Brief Report we show that asymmetric coupled quantum wells (ACQW's), in which two $In_{0.53}Ga_{0.47}As$ quantum wells of different thicknesses are coupled by a thin $In_{0.52}Al_{0.48}As$ tunnel barrier (see Fig. 1), exhibit significant electroabsorption effects even when the wells are relatively thin. Previously, we demonstrated that the coupling of the lowest-energy electron subbands in a $GaAs/Al_xGa_{1-x}As$ ACQW structure could be clearly observed in low-temperature photocurrent (PC) spectroscopy[4] and resulted in enhanced intensity and phase modulation in waveguides.[10] Here we report the results of room- and low-temperature PC measurements on two $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MQW samples: one containing uncoupled quantum wells and one containing the ACQW structure. We show that the shifts in the excitonic absorption peaks in the ACQW structure are large even for low biases, whereas the Stark shifts observed in the uncoupled-well sample are relatively small.

The $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ samples studied in this work were grown by molecular-beam epitaxy on n^+-type InP substrates at a growth temperature of 520 °C at a rate of 1.2 μm/h, with the group-V (As_4)–to–group-III beam-flux ratio maintained at about 5:1. The layer sequence for the samples, starting from the substrate, is as follows: 0.35 μm n^+-type ($\sim 2\times10^{18}/cm^3$ Si) $In_{0.52}Al_{0.48}As$; 0.15 μm undoped $In_{0.52}Al_{0.48}As$; 0.7 μm undoped MQW region; 0.15 μm undoped $In_{0.52}Al_{0.48}As$; 0.2 μm p^+-type ($\sim 2\times10^{18}/cm^3$ Be) $In_{0.52}Al_{0.48}As$; and a 20-nm p^+-type $In_yGa_{1-y}As$ contact layer. The total thickness of the intrinsic region is 1.0 μm. The control sample's MQW region has 40 periods of a 7.5-nm $In_{0.53}Ga_{0.47}As$ well plus a 10.0-nm $In_{0.52}Al_{0.48}As$ barrier. For the ACQW sample, the MQW region consists of 29 periods of the following structure: a 5.0-nm $In_{0.53}Ga_{0.47}As$ well, a 1.6-nm $In_{0.52}Al_{0.48}As$ tunnel barrier, a 7.5-nm $In_{0.53}Ga_{0.47}As$ well, and a 10.0-nm $In_{0.52}Al_{0.48}As$ barrier. The wells were grown with the narrow well closest to the n-type substrate so that an increasing reverse bias would tune the lowest-lying electron subbands through resonance (as shown in Fig. 1). X-ray-diffraction measurements showed that the indium mole fraction in the $In_{0.53}Ga_{0.47}As$ layers was 0.53±0.01, and that all other layer compositions and thicknesses were within 2% of their design values.

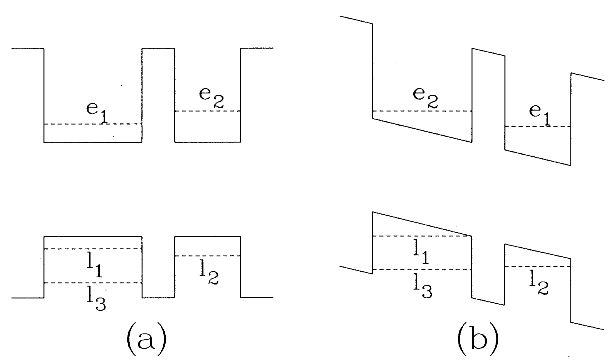

FIG. 1. Energy-band diagram (not to scale) for the asymmetric coupled-quantum-well system for (a) zero field and (b) a field for which the electron levels are beyond resonance. The electron and light-hole levels are labeled $e_{1,2}$ and $l_{1,2,3}$, respectively, where the subscripts are in order of increasing energy. Not shown are the heavy-hole levels, referred to in the text as $h_{1,2}$.

In the PC experiments, chopped light from a tungsten-filament lamp was dispersed by a 0.75-m, nitrogen-purged monochromator and focused onto a 250-μm-diam mesa diode fabricated from one of the samples. A current-sensitive preamplifier and a lock-in amplifier were used to detect the photocurrent generated in the diode as a function of the photon energy and the bias on the sample. For the low-temperature measurements, the samples were mounted in a continuous-flow, liquid-helium cold-finger cryostat, and the dispersed light was focused through a window in the cryostat onto the sample.

In Fig. 2 we show the room-temperature PC spectra of the control sample (containing uncoupled 7.5-nm wells) for reverse biases of 0, 3, 6, and 9 V applied to the sample. The "noise" at about 0.9 eV in the spectra arises from atmospheric absorptions. Both the h_1e_1 exciton, (a), and the l_1e_1 exciton, (b), exhibit small Stark shifts that depend quadratically on applied bias. The magnitudes of the observed shifts are consistent with single-band envelope-function calculations, indicating high-quality quantum wells with low deep-level and background doping densities.[5,6]

In Fig. 3 we show the room-temperature PC spectra for the ACQW sample at the same biases as in Fig. 2. The coupling in this sample is strong (in contrast with the GaAs/Al_xGa_{1-x}As ACQW sample reported earlier[4]) because of the thin (1.6-nm) barrier. Therefore, even a small change in bias results in significant changes in the photocurrent spectra. For example, at 3 V reverse bias the h_1e_1 exciton is shifted by almost 4 meV from the zero-bias energy, and a new transition begins to appear at about 0.88 eV.

The resonance and avoided-level crossing[4] of the e_1 and e_2 electron subbands occur at a reverse bias of about 5 V. Beyond resonance [see Fig. 1(b)], a feature of particular interest is the interwell transition that occurs between the lowest-energy heavy-hole subband in the wide well (h_1) and the lowest-energy electron subband in the narrow well (e_1). This transition has a substantial oscillator strength that persists over a wide range of applied biases and is easily observable at room temperature (see, e.g., the shoulder labeled (a) in the 9-V trace in Fig. 3; this transition has shifted by about 30 meV from its zero-bias energy). A comparison of Figs. 2 and 3 clearly reveals that the features observed in the ACQW sample arise from coupling between the wells. (Note that, at zero bias, the h_1e_1 exciton occurs at slightly lower energy in the control sample than in the ACQW. This discrepancy can be attributed to a difference of 0.015 in the In mole fractions of the $In_{0.53}Ga_{0.47}$As layers in the two samples.)

Figure 4 shows the 8-K PC spectra of the ACQW sample for applied reverse biases of 0, 3.5, 5, 6.5, and 10 V. These spectra were divided by the signal from a Ge photodiode (which monitored a fraction of the dispersed light) to minimize the effects of atmospheric absorptions. Dramatic effects of level splittings associated with the coupling of the e_1 and e_2 subbands are evident at low temperature, particularly near the resonance field (see, e.g., the 5-V spectrum in Fig. 4). Beyond resonance, the interwell transition, h_1e_1, is the lowest-energy optical transition supported by the system, and it can be observed for biases well beyond resonance (see, e.g., the 10-V spectrum in Fig. 4). This transition was responsible for a substantial enhancement of the below-band-gap electro-optic properties of GaAs/Al_xGa_{1-x}As ACQW waveguides,[10] and should play an important role in the development of practical devices in $In_{0.53}Ga_{0.47}$As ACQW systems.

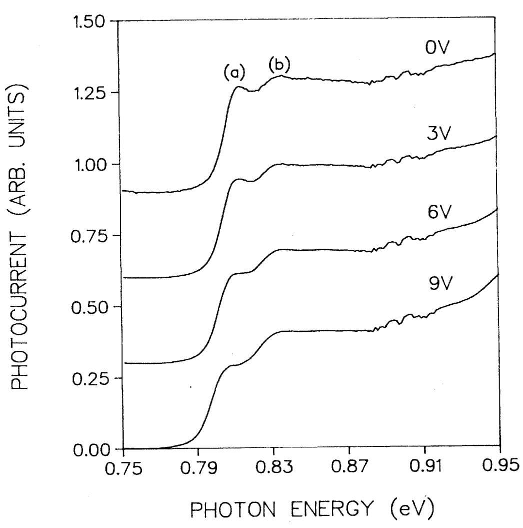

FIG. 2. Room-temperature photocurrent spectra of a sample containing 40 periods of 7.5-nm $In_{0.53}Ga_{0.47}$As quantum wells, for several values of reverse bias. Transitions are labeled as follows: (a) h_1e_1 and (b) l_1e_1. The "noise" in the spectra at about 0.9 eV is due to atmospheric absorptions. The spectra are offset vertically for clarity.

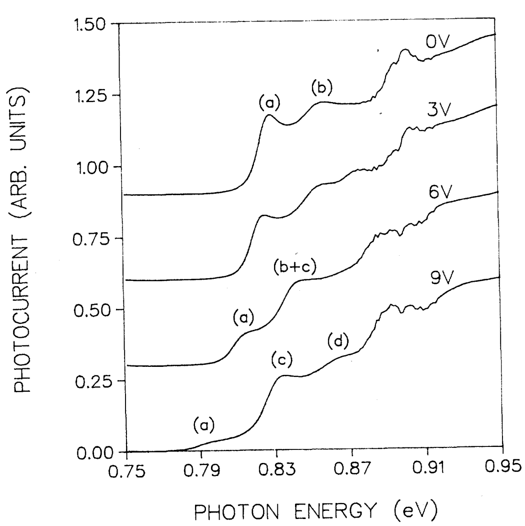

FIG. 3. Room-temperature photocurrent spectra of a sample containing 29 periods of 7.5- and 5.0-nm $In_{0.53}Ga_{0.47}$As quantum wells coupled by a 1.6-nm $In_{0.52}Al_{0.48}$As barrier, for several values of reverse bias. The transitions are labeled as in Fig. 2, with the addition of (c) h_1e_2 and (d) l_1e_2. Beyond resonance, h_1e_1 is an interwell transition. The spectra are offset vertically for clarity.

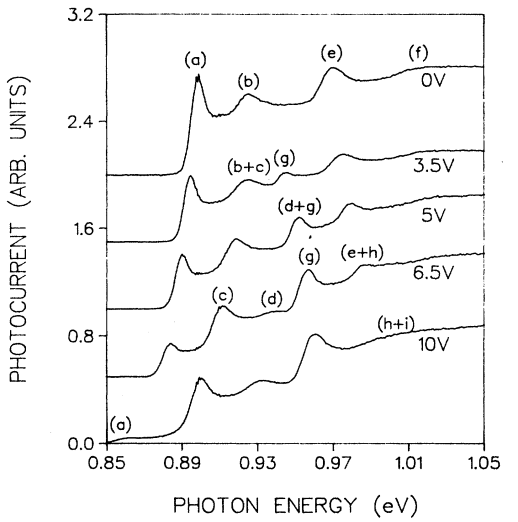

FIG. 4. Low-temperature (8-K) photocurrent spectra of the sample described in Fig. 3. The transitions are labeled as in Figs. 2 and 3, with the addition of (e) h_2e_2, (f) l_2e_2, (g) h_2e_1, (h) l_2e_1, and (i) l_3e_1. The spectra are offset vertically for clarity.

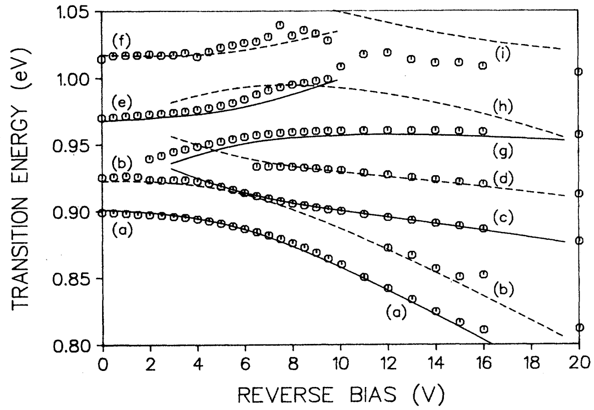

FIG. 5. Comparison of calculated and observed (at 8 K) transition energies for the ACQW structure. Transitions are labeled as in Figs. 2–4. Solid lines indicate heavy-hole transitions and dashed lines are light-hole transitions.

Figure 5 shows the peak energies (symbols) of several low-temperature excitonic transitions as a function of applied bias. The solid and dashed lines in Fig. 5 show the calculated energies of heavy- and light-hole transitions, respectively, that are expected to have significant oscillator strengths in the 0.8–1.05-eV energy range in this coupled-well system. The calculations were performed using the scattering phase-shift method,[11] where the transition energies are obtained as the peaks in the calculated density of states. Valence-band mixing and conduction-band nonparabolicity effects were neglected, and the following material parameters were used:[6] for $In_{0.53}Ga_{0.47}As$, $m_e=0.041$, $M_{lh}=0.0516$, and $m_{hh}=0.377$; for $In_{0.52}Al_{0.48}As$, $m_e=0.075$, $m_{lh}=0.085$, and $m_{hh}=0.57$. The valence- and conduction-band offsets were taken as 224 and 523 meV, respectively. Effective band gaps (including field-independent exciton binding energies) were chosen separately for light- and heavy-hole excitons to obtain the best agreement with the measured wide- and narrow-well transition energies at zero bias, thus allowing for small uncertainties in the In mole fraction and in strain-induced splitting of the light- and heavy-hole bands.

The electron subbands e_1 and e_2 come into resonance at a reverse bias of about 5 V, and transitions between the isolated heavy-hole subbands h_1 and h_2 (localized in the wide and narrow wells, respectively) to this coupled pair are apparent over a wide range of biases in Fig. 5. We could not follow the corresponding light-hole transitions over the entire bias range; they are weaker and broader than the heavy-hole transitions. We predict an avoided-level crossing of the l_2 and l_3 hole subbands [see Fig. 1(b)] at about 12–14 V, but the experimentally observed feature [labeled $(h+i)$ in the 10-V spectrum in Fig. 4] is very broad and cannot be resolved into two transitions. The agreement observed between theory and experiment is satisfactory, considering that the material parameters are not as well established for the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ system as for the $GaAs/Al_xGa_{1-x}As$ system. Calculations (not shown) for the higher-energy transitions do not agree as well with the experimental data (probably because we have neglected nonparabolicity in the conduction band), and thus positive identification of these transitions is not possible at present.

In summary, we have shown that it is possible to obtain large shifts in the energies of the excitonic absorptions in asymmetric coupled-quantum-well structures containing relatively thin wells, in which the normal QCSE is weak. Our low-temperature photocurrent results for the energies of several excitonic transitions involving the coupled pair of electron subbands associated with the two wells are in excellent agreement with calculations performed using a scattering-phase-shift method. In a future publication,[12] we plan to show that the avoided-level crossing of this coupled pair leads to enhanced amplitude and phase modulation in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ waveguides containing the ACQW structure.

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