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[11] We anticipate that there exist substantially greater numbers of dislocations that reside near the substrate/etalon interface. However, this interface is far removed from the half-wave layer that corresponds to the active layer in a practical device.

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# Coupled GaAs/AlGaAs quantum-well electroabsorption modulators for low-electric-field optical modulation

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Experimental and theoretical studies are presented for exciton transitions in *p-i-n* GaAs/AlGaAs multiple coupled-quantum-well structures where each quantum well consists of two identical wells with a thin barrier. Electroabsorption and photocurrent studies are carried out to identify how the excitonic peaks respond to transverse electric fields. With a careful choice of the dimensions of the coupled quantum well, it is seen that the lowest heavy-hole exciton peak moves at a rate ~2.5 faster than in a square well. Thus strong modulation is obtained at much lower electric fields. The nature of the higher-energy transitions is also studied.

Recently, a great deal of research has been carried out in the area of excitonic and band-to-band transitions in the presence of a transverse electric field.[1-6] A number of optical devices has also been studied which are based on the resulting quantum-confined Stark effect[1] in the multiquantum wells (MWQ). All-optical and electro-optical switches and modulators have been conceived and fabricated using *p-i*(MQW)*-n* structures with appropriate circuitry.[7-9] An important consideration in all these devices is the rate at which the exciton transitions shift in energy with electric field. This rate can be increased by increasing the well size, but for large electric fields, the excitonic binding energy and absorption coefficient decrease rapidly, thus reducing the benefits of strong optical modulation. Currently, optical modulators are fabricated from uncoupled square quantum wells and the Stark effect remains quadratic in these wells up to fairly high electric fields. For a 100-Å GaAs/AlGaAs MQW structure, an electric field of ~70 kV/cm is required to shift the lowest heavy-hole (hh) exciton peak by 15 meV. Since at least a 1-μm intrinsic MQW region is required for a large contrast ratio, a voltage of ~7–8 V is required. It is difficult to obtain such large drives if high-speed (~GHz) electronic circuitry is to be used for controlling the modulator state. It is thus important to examine other quantum-well shapes to increase the rate of shift of exciton peak.

Some work has been done on the optical properties of coupled quantum wells,[10-12] but their potential for low bias modulation has not been explored. In this communication we present the first results of theoretical and experimental studies on a multiple coupled-quantum-well (MCQW) structure where each quantum well consists of two identical quantum wells separated by a small, thin AlGaAs barrier.

Figure 1 shows the calculated lower-lying electron- and hole-state wave functions in the coupled and square well at electric fields of 0 and 50 kV/cm. Figures 1(a) and 1(c) are for the wave functions of the coupled quantum well without and with electric field, and Figs. 1(b) and 1(d) are for a 100-Å square well under similar biasing conditions. An important point to note is the electron and hole wave functions at finite electric fields. In the square quantum well, as can be seen from Figs. 1(b) and 1(d), the wave functions are not seriously distorted with applied fields. One result of this relatively small distortion and even parity of the ground-state functions is a negligible linear Stark effect at low fields. On the other hand, in the coupled quantum well with properly chosen dimensions, the wave functions are seriously distorted [compare Fig. 1(a) and 2(c)], leading to much larger electric field dependence of subband levels and oscillator strengths.

For the modulation experiments, *p-i-n* diodes with coupled-quantum-well undoped *i* regions were grown by molecular-beam epitaxy (MBE) on GaAs substrates. The struc-

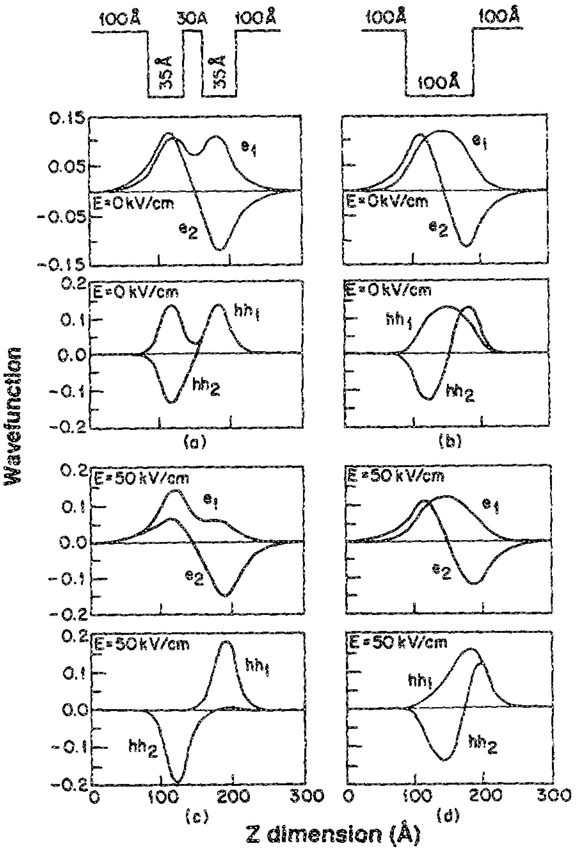

FIG. 1. Electron and hole wave functions in coupled- (100-Å well with 30-Å inside barrier) and square-quantum-well (100-Å) structures at 0 and 50 kV/cm. (a) and (c) are for the coupled well, and (b) and (d) are for the square well.

ture consists of an initial 1000-Å Si-doped ($2\times10^{18}$ cm$^{-3}$) GaAs smoothening layer followed by 0.5-$\mu$m Si-doped $Al_{0.4}Ga_{0.6}As$ ($2\times10^{18}$ cm$^{-3}$) as an etch-stop layer, 50 periods of Si-doped ($2\times10^{18}$ cm$^{-3}$) GaAs(15 Å)/$Al_{0.3}Ga_{0.7}As$(20 Å) superlattice (SL), 20 periods of undoped GaAs(15 Å)/$Al_{0.3}Ga_{0.7}As$ (20 Å) SL, 50 periods of the undoped coupled quantum well, the two smoothening superlattices (20 periods and 50 periods) in reverse order and the top one doped $p$ type ($2\times10^{18}$ cm$^{-3}$), and finally 0.2-$\mu$m Be-doped ($2\times10^{18}$ cm$^{-3}$) $Al_{0.4}Ga_{0.6}As$ and 100-Å Be-doped ($2\times10^{18}$ cm$^{-3}$) GaAs for contacting. The coupled well consists of two 35-Å GaAs wells coupled by a 30-Å $Al_{0.2}Ga_{0.8}As$ barrier. In the MCQW the coupled wells are separated from each other by 100-Å $Al_{0.2}Ga_{0.8}As$ barriers. The entire structure is grown at 630 °C at a rate of ~1 $\mu$m/h.

500-$\mu$m-diam mesa-etched *p-i-n* diodes were used for the electrabsorption and photocurrent measurements. Evaporated and alloyed Ti/Au and Ni/Ge/Au contacts were formed on the $p^+$ and $n^+$ layers, respectively. For electroabsorption measurements, a hole was etched in the $n^+$ substrate GaAs layers with a preferential (GaAs/AlGaAs) etchant using the jet-thinning technique. The electroabsorption measurements were made by illuminating the back hole with focused light from a tungsten-halogen source and analyzing the transmitted light with a 1-m spectrometer. Photocurrent spectra were recorded by illuminating the diode with monochromatic light from a 1-m spectrometer.

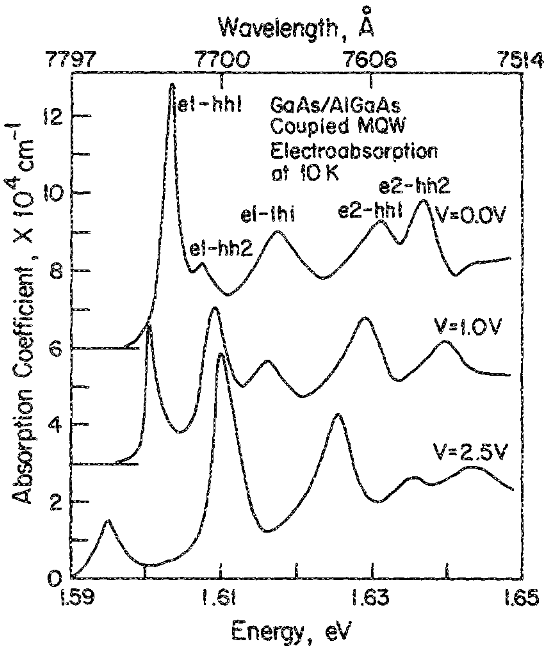

FIG. 2. Electroabsorption spectra for the coupled-quantum-wells at applied bias of 0, 1, and 2.5 V.

Figure 2 shows the results of electroabsorption studies in the *p-i*(MCQW)-*n* for applied biases of 0, 1.0, and 2.5 V. Note the sharp exciton transitions which are representative of the high level of perfection obtained in the MBE growth. Ground-state exciton linewidths are ~5 meV at room temperature and 3.5 meV at 15 K. As can be expected from Fig.

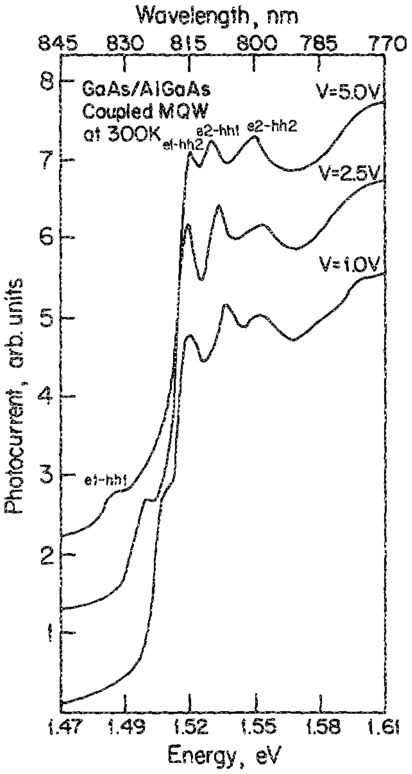

FIG. 3. Photocurrent spectra for the coupled-quantum-well MQW structure at different biases.

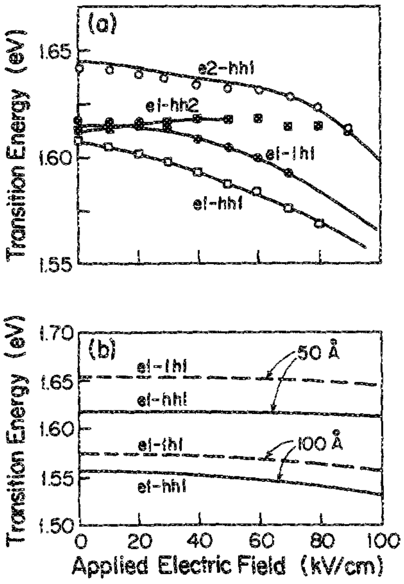

FIG. 4. (a) Experimental and theoretical positions of various peaks observed from photocurrent as a function of applied bias; (b) electric field dependence of transitions in a 50- and 100-Å square well.

1, the ground-state transition decreases rapidly in intensity and also moves to lower energies at low applied bias values. It is interesting to note the behavior of the excitonic absorption peak due to an $e1$-hh2 transition. While the energy for this transition does not change with applied field, its strength increases sharply in contrast to this $e1$-hh1 transition. This transition will thus have important application for spatial light modulators. Figure 3 shows the results of photocurrent spectroscopy at room temperature. Once again we see sharp peaks corresponding to excitonic transitions in the coupled quantum wells. Room-temperature electroabsorption data show the same features.

Finally, Fig. 4(a) shows the shift of several peak positions in the coupled-well structure as a function of electric field. Also shown as solid lines are the calculated values of these shifts. The calculations, based on an eigenvalue method for the ground states, are shown up to the highest fields measured, while the excited-state results are shown only up to 60 kV/cm because of uncertainties in the quasibound hh2 state at very high fields. The agreement between theory and experiments is quite remarkable. For comparison Fig. 4(b) shows the shifts in exciton peaks for a 50-Å square quantum well (selected because the hh peak is at the same energy position as for the coupled quantum well) and a 100-Å square well as a function of electric field. The ground state in the coupled well moves at a rate which is an order of magnitude faster than a 50-Å well and about 2.5 times faster than the rate in a 100-Å square well. For a comparable shift in the ground-state exciton peak, the coupled quantum well needs much smaller biasing compared to the square well. As explained earlier from Fig. 1, the rapid shift is due to the large change in the $e$-hh overlap function in the coupled quantum well.

In summary, we have studied electroabsorption and photocurrent phenomenon in MCQWs. The rapid shift in the energy for the lowest exciton transition suggests important low-field-modulation applications for these structures. Other exciton transitions in MCQW structures may also be important for this application and their details will be published shortly.

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