# Electroabsorption in GaAs/AlGaAs coupled quantum well waveguides

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A novel GaAs/AlGaAs coupled quantum well structure, consisting of two 46 Å wells separated by a 11.5 Å barrier, was embedded in a leaky waveguide. Polarization anisotropy and quantum-confined Stark effect absorption changes are observed, and a 14:1 modulator is demonstrated operating at the peak of the first light-hole transition. Although the lowest energy transitions behave as predicted by tunneling resonance calculations, higher energy states exhibit unusual behavior due to valence-band mixing.

Quantum well structures have recently stirred considerable interest because they show well-resolved excitons at room temperature,[1] they have enhanced nonlinear cross sections,[1,2] and they exhibit the quantum-confined Stark effect (QCSE),[3,4] among other properties. Most optical studies to date have dealt with rectangular quantum wells where a ~100-Å GaAs layer is sandwiched between ~100 Å AlGaAs barriers. In contrast, we present a novel coupled quantum well (CQW) structure in which the ~100 Å GaAs is replaced by two narrow GaAs wells coupled by a thin AlGaAs barrier between them. Since the hole and electron can tunnel through the thin barrier, the wave functions are shared between both wells, and the distribution can be adjusted by applying an electric field to tilt the bands. The measured CQW optical properties exhibit the QCSE and polarization anisotropy,[5-7] and a 14:1 modulator is demonstrated. Higher lying transitions in the CQW behave unusually because of valence-band mixing.[8,9]

Through computer simulations we designed the CQW so that a large absorption change could be achieved by varying the overlap between the hole and electron wave functions with an applied electric field. As Fig. 1(a) illustrates, when two narrow wells are coupled, they form symmetric and antisymmetric wave functions. Application of an electric field can skew the hole to one side and the electron to the other [Fig. 1(b)], greatly reducing the overlap between the symmetric wave functions. In principle, the reduction in overlap with this kind of structure may be larger than that of a comparable rectangular well.

The experiments were performed using 150-$\mu$m-long leaky waveguide samples[5-7] [Fig. 1(a)]. The CQW consisted of two 46 Å GaAs wells separated by a 11.5 Å AlGaAs barrier. Two such CQW's were embedded at the center of a 4.1-$\mu$m-thick superlattice which formed the waveguide core; the superlattice was surrounded by GaAs cladding layers. The sample was doped as a *p-i-n* diode so that an electric field could be applied perpendicular to the quantum wells. Apart from the use of the CQW, this structure is similar to a recently demonstrated low-voltage QCSE waveguide modulator.[6]

A styryl 9 dye laser was used as the light source for the experiments. The laser beam was spatially filtered to guarantee a lowest order Gaussian mode, and then focused into the sample using laser diode collimating objectives. Care was taken to minimize coupling to higher order waveguide modes. We refer henceforth to the "parallel (perpendicular) polarization" when the electric field of the optical wave is polarized parallel (perpendicular) to the plane of the layers.

The measured absorption spectra, plotted versus energy in Fig. 2 for different applied voltages, exhibit the polarization anisotropy previously observed.[5,6] The electric field strength can be calculated from the applied voltage, known sample thickness, and estimated built-in field. However, for reasonable agreement with theory (cf. Fig. 3) we must further subtract off a "dead field" of $5\times10^4$ V/cm. Although the origin of this correction is unclear, it is common also for rectangular quantum wells.[7]

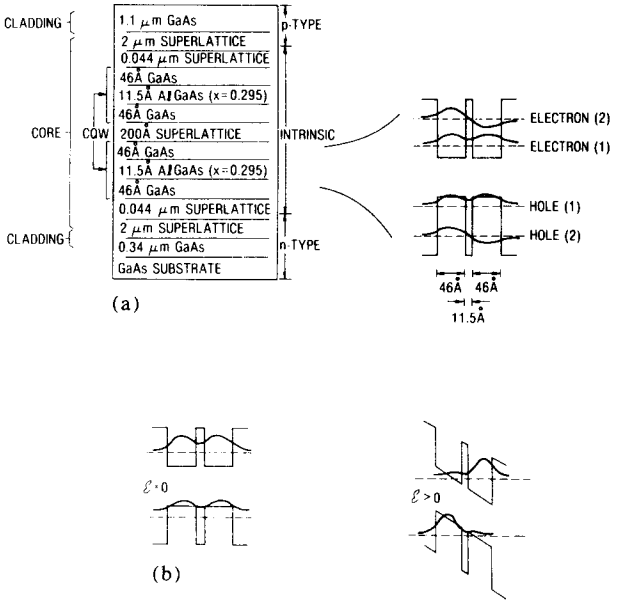


FIG. 1. (a) Sample structure and schematic of first and second transitions in the CQW. The superlattice consists of alternating layers of 21 Å GaAs and 34 Å $Al_xGa_{1-x}As$ ($x = 0.295$). The $n$ and $p$ dopings are $10^{18}$ cm$^{-3}$, except in the top 0.1 $\mu$m of GaAs which is $p$ doped at $10^{19}$ cm$^{-3}$. (b) For sufficient electric field applied perpendicular to the layers, the hole can shift to the left well and the electron to the right, thus reducing the overlap between the wave functions.

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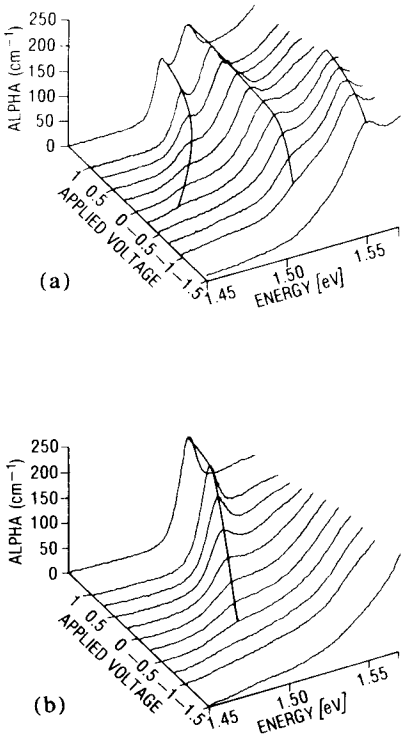


FIG. 2. Measured absorption spectra as a function of energy for different voltages applied perpendicular to the quantum wells. Electric field for the optical wave is polarized (a) parallel to and (b) perpendicular to the CQW layers. The lines connecting the peaks are drawn as a guide to the eye. The adjusted field is calculated by using the estimated built-in field and allowing for a "dead field" of $5\times10^4$ V/cm [$E(\text{V/cm}) \cong -77.76\times10^3\ \text{V} + 8\times10^4$].

We have made a 14:1 modulator in the perpendicular polarization by working at the zero field *lh* 11 peak ($E = 1.525$ eV) and varying the applied voltage between $+1.1$ and $-2.4$ V. Optical bistability has also been demonstrated by using the CQW structure as a self-electro-optic-effect device (SEED).[10] The broadening of the absorption

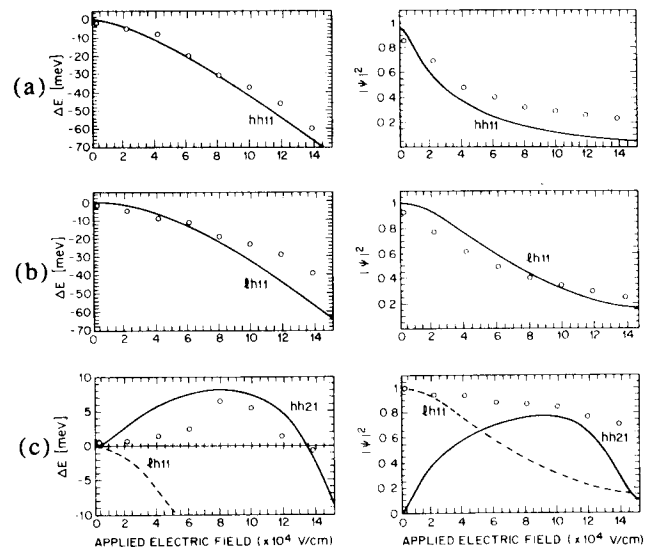


FIG. 3. Energy shift and change in overlap plotted vs applied electric field for (a) first parallel polarization transition, (b) first perpendicular polarization transition, and (c) second parallel polarization transition. The solid and dashed curves are from tunneling resonance calculations, while the circles correspond to measured data corrected for the "dead field."

features does in practice limit the minimum attainable absorption, but this modulator performance is comparable to or better than the best rectangular well waveguide modulators.[5–7]

In the perpendicular polarization [Fig. 2(b)], only the light-hole transitions exist because selection rules prohibit any heavy-hole transition.[11] The first light-hole-to-electron (*lh* 11) transition shifts to lower energies and decreases in strength with increasing field. In the parallel polarization, three transitions are resolved clearly. The lowest energy resonance corresponds to the first heavy-hole-to-electron (*hh* 11) transition, and its behavior is qualitatively similar to *lh* 11.

In typical quantum well samples the second, higher energy transition in the parallel polarization generally has lower peak absorption than the first.[1,5,6] For $\sim 100$ Å wells the lowest energy *hh* 11 and *lh* 11 exciton peaks are separated at zero field by $\Delta E \sim 10$ meV. Since $\Delta E$ is of the order of the *hh* 11 exciton binding energy, the *lh* 11 transition is only slightly superimposed on the *hh* 11 continuum and the *hh* 11 ends up with a higher peak absorption. In contrast, due to increased confinement energies in the CQW, our sample has $\sim 17$ meV separation between *hh* 11 and *lh* 11, so that the latter sits on top of the *hh* 11 continuum. This explains why the second transition in Fig. 2(a) has higher absorption than the first.

The second transition in Fig. 2(a) coincides with the zero field position of *lh* 11; however, it shifts at first to higher energies with increasing field [Fig. 3(a)]. This shift behavior is characteristic of the second-heavy-hole-to-first-electron transition (*hh* 21), except that *hh* 21 should be forbidden at small fields (whereas the observed transition is quite strong even at zero field). This can be rationalized as follows. At low fields in the parallel polarization, the second peak is indeed *lh* 11. With increasing field the *lh* 11 becomes weaker (it is already relatively weak in this polarization) and *hh* 21 starts to become allowed. As *hh* 21 dominates the spectrum in this region, we obtain the observed shift behavior. However, as discussed below, mixing of the valence-band states should be accounted for to explain the overall behavior of this transition.

A third transition for the parallel polarization increases in strength and shifts to lower energy with increasing field. It should be heavy hole in character since it does not appear in the perpendicular polarization. Also, it is a forbidden transition which becomes allowed with increasing field. We have not positively identified this resonance because its position does not coincide with calculated energies for any heavy-hole transition.

For comparison with theory, we performed tunneling resonance calculations,[3,4] which are exact computer solutions of the Schrödinger equation in the effective mass approximation. The appropriate parameters for the computations were taken from Ref. 4, assuming a 57:43 split between the conduction- and valence-band discontinuities. A 256 point mesh was used to simulate the 46-11.5-46 Å CQW, and we solved both for the transition energies and wave functions. At each interface we required continuity of the wave function and particle flux.

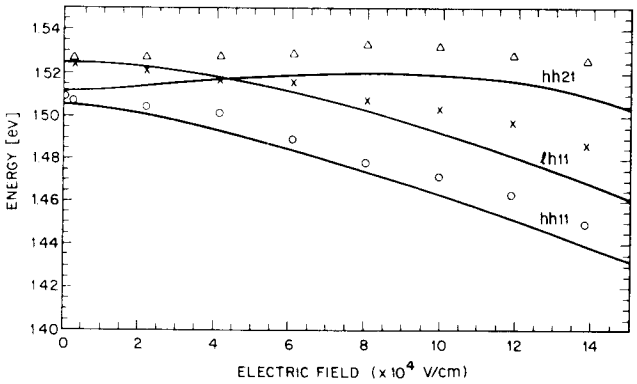


FIG. 4. Calculated and measured transition energies vs applied electric field. The solid lines are from tunneling resonance calculations, while the symbols are measured data (○ = first parallel polarization transition, × = first perpendicular polarization transition, and △ = second parallel polarization transition).

Figure 3 compares the measured energy shifts and absorption strengths (i.e., peak absorptions) with calculations. We presume that the strength follows the square of the single particle electron and hole wave function overlap integral. This is reasonable if the peaks do not broaden with field and if higher lying excitonic states are neglected.[7] For the first transition in both polarizations, there is reasonable agreement with theory, given the uncertainties in the structure parameters. In Fig. 3(c) we present calculations for *lh* 11 and *hh* 21 along with data for the second parallel polarization transition. Although the data do not follow either theoretical curve, there is a hint that the state starts out *lh* 11 and changes over to *hh* 21.

That valence-band mixing should occur is evident from Fig. 4, where we plot the calculated and measured transition energies. These simplistic calculations show that around $E_c = 4.4\times10^4$ V/cm the *hh* 21 and *lh* 11 transitions would intersect. Therefore, one expects that a state which is *lh* 11-like for $E<E_c$ may behave like *hh* 21 for $E>E_c$. Near $E_c$, of course, the behavior can be quite complicated. Our calculations treat the heavy and light holes separately, and we have not attempted to solve for the wave functions of the mixed states.[8,9] The crossing of the transitions and the particular field at which it occurs appear to be a consequence of the 46-11.5-46 Å structure, rather than any fundamental property of CQW's. The intersection occurs at relatively low energy in the CQW because the *hh* 1 (symmetric) and *hh* 2 (antisymmetric) wave functions lie close in energy.

In summary, we have studied the linear optical properties of a novel coupled quantum well structure which was embedded in a leaky waveguide. The structure exhibits both polarization anisotropy and the QCSE, and was used as a modulator with 14:1 on:off ratio. This demonstrates explicitly that structures other than rectangular wells can show useful QCSE, offering a new degree of freedom in device design. These structures also show unusual behavior of higher transitions that may reflect complex behavior of valence-band states.

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[11]The interband oscillator strengths for the parallel and perpendicular polarizations are $f_{\|}(hh)=3/4$, $f_{\|}(lh)=1/4$, $f_{\perp}(hh)=0$, and $f_{\perp}(lh)=1$.