RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 48, NUMBER 11 15 SEPTEMBER 1993-I

# Piezoelectric-field effects on transition energies, oscillator strengths, and level widths in (111)*B*-grown (In,Ga)As/GaAs multiple quantum wells

R. A. Hogg, T. A. Fisher, A. R. K. Willcox, D. M. Whittaker, M. S. Skolnick, and D. J. Mowbray
*Department of Physics, University of Sheffield, Sheffield, S3 7RH, United Kingdom*

J. P. R. David, A. S. Pabla, G. J. Rees, R. Grey, J. Woodhead, J. L. Sanchez-Rojas,*
G. Hill, M. A. Pate, and P. N. Robson
*Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, S1 4DU, United Kingdom*
(Received 1 June 1993)

We report a spectroscopic study of high-quality piezoelectric (PZ) (111)*B* GaAs/(In,Ga)As strained multiple quantum wells. Normally forbidden $\Delta n \neq 0$ transitions ($E1$HH2, $E1$HH3, $E2$HH1) are observed strongly due to the asymmetric well profile induced by the PZ field. Applying a bias to oppose the PZ field reduces the quantum-confined Stark shifts and weakens the $\Delta n \neq 0$ transitions. At high bias, corresponding to flat band in the well, strong lifetime broadening is observed. Good agreement between theory and experiment is found, but only by using a value for the PZ constant ~30% smaller than the commonly accepted value.

There has been considerable recent interest in the optical and electronic properties of strained-layer quantum-well (QW) structures grown in the (111) polar direction.[1-7] The zinc-blende structure lacks inversion symmetry, so that strain in the (111) direction produces significant piezoelectric (PZ) fields in the wells ($\sim 2\times 10^5$ V/cm in $In_{0.15}Ga_{0.85}As$/GaAs QW's).[1] As a result, these structures experience a strong quantum-confined Stark effect (QCSE) without any external field.[2] This has been demonstrated both by the application of an opposing bias, producing a large blueshift of the transition energies,[3,5] and by nonlinear optical behavior when photoexcited carriers screen the internal fields.[4,5]

In this paper we present an experimental and theoretical investigation of the optical properties of a series of high-quality samples in which a number of PZ (In,Ga)As/GaAs multiple QW's (MQW's) are embedded in the intrinsic region of a *p-i-n* structure. Both photoluminescence excitation (PLE) and photocurrent (PC) spectroscopies are used to measure the low-temperature ($T=4$ K) absorption characteristics as a function of applied bias. Up to four prominent optical transitions are observed in the spectra, including $\Delta n \neq 0$ lines[6] of comparable strength to the $\Delta n=0$ transitions. As the applied bias opposing the PZ field is increased, the QCSE is reduced, weakening the $\Delta n \neq 0$ transitions, until only $E1$HH1 remains strong when the well profile is flat.[2,7] However, the field in the barriers is still large, leading to significant lifetime broadening of the exciton peak. Solutions to Schrödinger's equation support our interpretation of the results and show that the growth parameters are close to their nominal values. However, the fits suggest a value for the PZ constant $e_{14}$ ($0.097\pm 0.015$ C/m$^2$), considerably smaller than previously determined.[8]

The samples were fabricated by molecular-beam epitaxy and grown on (111)*B* semi-insulating GaAs substrates oriented 2 degrees toward (001). The layers, in order of growth, consist of 2.5-$\mu$m $n^+$-type GaAs (dopant Si), 0.625-$\mu$m intrinsic region in which the (In,Ga)As/GaAs MQW's are incorporated centrally in GaAs, and 0.3-$\mu$m $p^+$-type GaAs (dopant Be). The nominal well width was 100 Å and indium concentration was 15%. Samples *A*, *B*, and *C* contain 17, 14, and 9 QW's, respectively, with barrier widths of 150 Å. Sample *D* has 5 QW's and barrier widths of 900 Å.[9] Transmission electron microscopy (TEM) measurements indicate well widths close to 100 Å with variations of ±10 Å for different structures in the series.

Figure 1(a) shows PL (dotted) and PLE (full line) spectra obtained from the unprocessed sample *A* (17 MQW's). The sample is of high quality, comparable to the best (100) structures.[11] This is indicated by the narrow PL and lowest-energy PLE linewidths of 4.5 and 3.2 meV, respectively, and by the very small Stokes shift between the PL peak and the lowest-energy PLE peak (<0.5 meV).[12] PC spectra are also shown in Fig. 1 from the processed structures sample *A* [17 MQW's, Fig. 1(b)], sample *B* [14 MQW's, Fig. 1(c)] and sample *D* [5 MQW's, Fig. 1(d)] at a bias of $V_a=-2$ V. The measurements were taken using 100 mW/cm$^2$ of radiation, but varying the power from 10 mW/cm$^2$ to ~5 W/cm$^2$ does not affect the observed spectra, showing that photoexcited carrier screening effects are not significant.

Four prominent excitonic transitions are observed in the PLE and PC of Fig. 1. The identifications are confirmed by solutions of Schrödinger's equation. The lowest-energy transition ($E1$HH1) involves absorption between the first heavy-hole state (HH1) and the first electron state ($E1$). The transitions to higher energy are $E1$HH2, $E1$HH3, and $E2$HH1. Calculated transition energies are marked by arrows on Fig. 1(a). Strain is expected to cause the light-hole transitions to become type II. Therefore, they will be upshifted by ~30 meV and are expected to be weak,[7-11] and as a result do not appear in the PC and PLE of Fig. 1.

A shift of the excitonic absorption peaks to higher en-

 ©1993 The American Physical Society

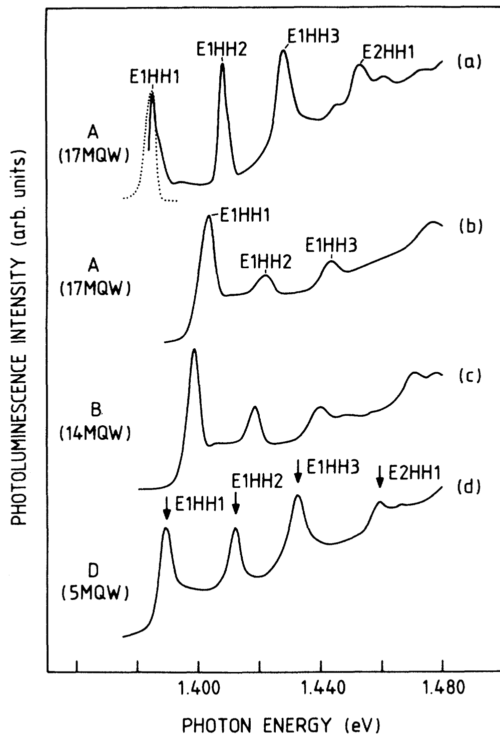


FIG. 1. PL (dotted line) and PLE (full line) spectra from sample $A$ (17 MQW's) at $T=4$ K in (a). Low-temperature PC spectra at $V_a=-2$ V are shown for (b) sample $A$ (17 MQW's), (c) sample $B$ (14 MQW's), and (d) sample $D$ (5 MQW's). The spectra show $\Delta n \neq 0$ transitions $E$1HH2, $E$1HH3, and $E$2HH1 of comparable strength to $E$1HH1.

ergy (18 meV for $E$1HH1) is observed in PC at low bias [Fig. 1(b)] compared to the PLE spectrum [Fig. 1(a)]. This difference arises because the unprocessed sample $A$, which is in the open circuit condition, experiences a photovoltage which approaches the band gap of around +1.5 V, whereas the PC spectrum from the processed sample $A$ is taken at an applied bias of $V_a=-2$ V. The difference in PC and PLE transition energies agrees well with shifts in the PC spectra with increasing bias, where a roughly linear upshift in energy of 5 meV/V is observed near $V_a=0$.

In Fig. 1(a) the $\Delta n \neq 0$ transitions $E$1HH2, $E$2HH1, and $E$1HH3 are of comparable strength to the allowed transition $E$1HH1. This arises from the strong internal PZ field.[1,2] These transitions are prominent in all of the structures measured, near $V_a=0$. The PC spectra in Figs. 1(b), 1(c), and 1(d) from samples $A$ (17 MQW's), $B$ (14 MQW's), and $D$ (5 MQW's) are taken at the same external bias of $V_a=-2$ V. As the number of wells in the intrinsic region is reduced from 17 to 5 the excitonic transitions move to lower energy ($E$1HH1 decreasing from 1.4034 to 1.3895 eV), corresponding to an increase in electric field. The electric fields of the wells ($E_w$) and barriers ($E_b$) are determined by two factors. First, the total potential drop across the well region, of total thickness $nL_w$ and the barrier region of thickness $L_{\text{in}}-nL_w$, is given by the sum of the built-in voltage $V_{pn}$ and the applied voltage $V_a$. Thus $(V_a+V_{pn})=E_w nL_w + E_b(L_{\text{in}}-nL_w)$ where $L_{\text{in}}$ is the width of the intrinsic region and $n$ the number of wells. Second, the well, barrier fields, and PZ field are related by $E_p=E_w-E_b$ which thus gives

$$E_w=\frac{(V_a+V_{pn})+(L_{\text{in}}-nL_w)E_p}{L_{\text{in}}} . \tag{1}$$

This equation demonstrates that for our structures, at a particular $V_a$, as the number of QW's is decreased, the magnitude of $E_w$ increases, leading to the observed reduction in the excitonic transition energies. The effects of the number of wells on $E_w$, and hence the excitonic transition energies, in 300-K PC spectra of these structures was reported recently.[10]

PC spectra as a function of applied bias $V_a$ are shown in Fig. 2 for sample $D$ (5 MQW's). A strong increase in the energy of the excitonic transitions of 16 meV is seen as the bias is increased from $V_a=-2$ to $-8$ V. This is also shown in the plot of the PC transition energies (filled circles) against bias in Fig. 3. As the field in the well is reduced the QCSE (Refs. 14 and 15) is reduced causing the observed blueshift. The turning point in the graph, corresponding to flat band in the well, occurs at $V_a=-8$ V. At low bias, $V_a=-2$ V [Fig. 2(a)], the $\Delta n \neq 0$ transitions $E$1HH2 and $E$1HH3 are of similar strength to the $\Delta n=0$ transition $E$1HH1.[6] Increasing the reverse bias leads to a clearly observed reduction in the strength of $\Delta n \neq 0$ transitions $E$1HH2 and $E$1HH3 as the field in the

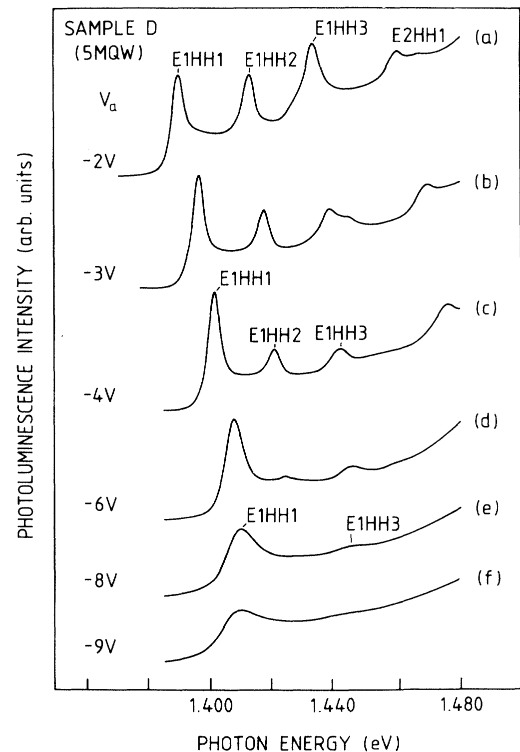


FIG. 2. PC as a function of applied bias for sample $D$ (5 MQW's). With increasing reverse bias the strength of the $\Delta n \neq 0$ transitions decreases, until at flat band in the well, $V_a=-8$ V (e) only $E$1HH1 is strongly observed.

RAPID COMMUNICATIONS



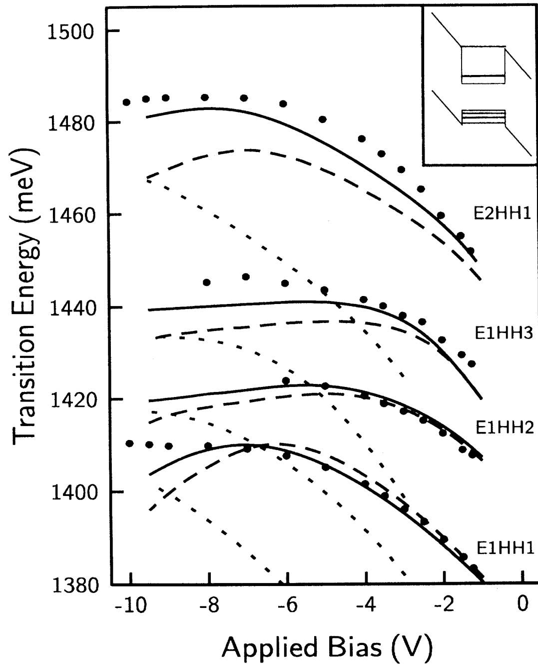


FIG. 3. Experimental transition energies (circles) as a function of applied bias for sample *D*. The lines are theoretical fits using various sets of parameters (see text for details). The inset shows the band profile at $V_a = -8$ V, where the well is flat.

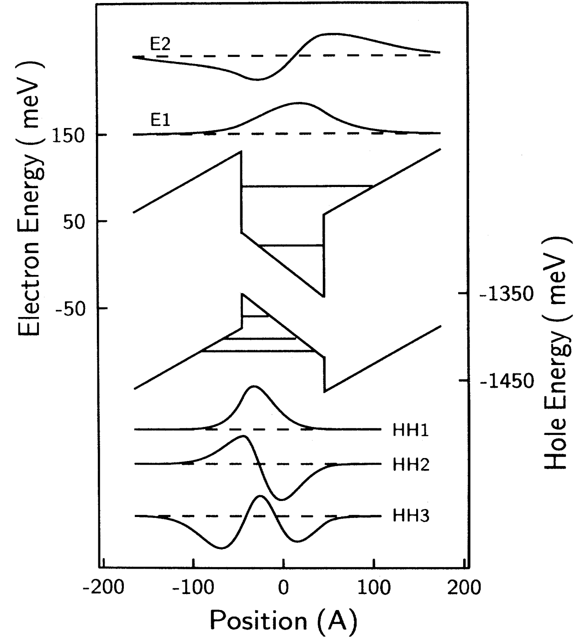


FIG. 4. Potential profile for one of the wells in sample *D* (5 MQW's), calculated at $V_a = -2$ V, along with energy levels and associated wave functions of the first few states.

well is reduced. By $V_a = -8$ V, $E1$HH2 is not observable and $E1$HH3 is very weak, as expected for a flat band in the well. A further trend observed with increasing bias, above $V_a = -5$ V, is for all excitonic transitions to undergo a strong broadening with only very broad features apparent at $V_a = -9$ V [Fig. 2(f)].

In order to interpret the experimental results in more detail the transition energies and oscillator strengths have been calculated as a function of $V_a$, using numerical solutions to Schrödinger's equation. In the calculations, standard interpolated values of the elasticity parameters and deformation potentials[8] were used to evaluate the effects of the strain on the band structure and to calculate the PZ field.[16] The (In,Ga)As electron mass was taken to be $0.067m_0$ (Ref. 17) and the heavy-hole mass along (111) to be $m_{\mathrm{HH}} = (\gamma_1 - 2\gamma_3)^{-1} m_0 = 0.7m_0$.[6,13]

Figure 4 shows a typical potential profile for one of the wells in sample *D* (5 MQW's), calculated at $V_a = -2$ V, along with energy levels and associated wave functions of the first few states. At this bias, the heavy-hole states HH2 and HH3 and electron state $E2$ are confined by the sloping barriers[7] which means that the confining potential is wider for HH3 than the lower hole states. As a consequence, at low bias the energy separation of $E1$HH1 and $E1$HH2 is greater than that of $E1$HH2 and $E1$HH3, while at $V_a = -8$ V the spacing is reversed.

Three fits to the experimental transition energies (circles) as a function of $V_a$ for sample *D* are shown in Fig. 3, using various values of the PZ constant $e_{14}$, well width, and indium concentration. 7 meV has been subtracted from all the calculated energies to allow for the exciton binding energy. The short-dashed line uses the standard value of $e_{14} = 0.143$ C/m$^2$,[8] linearly interpolated for the alloy, with nominal values of well width (100 Å) and indium concentration ($x = 0.15$), giving a piezoelectric field $E_p = 227$ kV/cm.[3] The agreement with experiment is very poor. In order to improve the fit, $e_{14}$ and $x$ were varied using this well width; reducing $e_{14}$ moves the curves toward zero bias, while reducing $x$ shifts the transition energies upwards. The value of $x$ is determined by fitting to the $E1$HH1 energy (1.410 eV) around $V_a = -8$ V, where the bottom of the well is flat and the transition energy is relatively insensitive to other parameters.[18] An optimum fit, shown by the long dashes, is obtained for $e_{14} = 0.088$ C/m$^2$ and $x = 0.145$ ($E_p = 140$ kV/cm). Although this gives good agreement for $E1$HH1, the energies of the higher transitions are still well below the experimental values. The best fit (solid lines), which agrees very well with experiment, was obtained by reducing the well width to 90 Å and using $e_{14} = 0.097$ C/m$^2$ with $x = 0.15$ ($E_p = 155$ kV/cm). The error in the $e_{14}$ determination is estimated to be ±10%, most of the uncertainty arising from the precision with which the flat band voltage can be located in Fig. 3.

The values of $e_{14}$ used in the better fits are much smaller than the standard value of 0.143 C/m$^2$. The lower values of $e_{14}$ are necessary in order to make the bias which gives flat wells agree with the experimentally observed maximum in the transition energies. However, a similar result would be obtained if the intrinsic region were narrower than its nominal width of 6250 Å. Although capacitance-voltage measurements suggest that this is not the case, there is sufficient uncertainty to prevent the fits being a definitive determination of $e_{14}$.[19] Very similar variations of transition energy against bias are observed for other samples in the series, except for a

shift along the voltage axis. This shift can be well explained using the same values of $e_{14}$ as for the five-well sample *D* and taking into account the larger number of wells as in Eq. (1).[10]

The calculated lifetime broadening only becomes significant in comparison with inhomogeneous broadening at biases beyond about $V_a = -6$ V where the barrier fields are high, but the well profile is close to flat band (Fig. 3 inset). At $V_a = -9$ V [Fig. 2(f)], where features can still be seen, the calculated broadening is 4.5 meV. The experimental linewidth changes from 6 meV at $V_a = -2$ V to 16 meV at $V_a = -9$ V, an increase of 10 meV. This is considered as good agreement, since the calculations are very sensitive to the input parameters. Increases in linewidth due to field variations in the structure at high $V_a$ are not a likely explanation for the results of Fig. 2(f) since near $V_a = -8$ V the transition energy does not vary greatly with bias (Fig. 3). At $V_a = -8$ V, for sample *D* (5 MQW's), the calculations predict that, because the bottom of the well is flat, *E*1HH2 and *E*2HH1 are very weak and *E*1HH3 has only 3% of the strength of *E*1HH1, in agreement with the spectra of Fig. 2(e). As the reverse bias is reduced and the field in the well becomes larger, the $\Delta n \neq 0$ transitions are predicted to become stronger, until at $V_a = -2$ V, *E*1HH2 and *E*1HH3 are of comparable strength to *E*1HH1, again in good qualitative agreement with the spectra of Fig. 2(a).

In conclusion, the variation of transition energies and oscillator strengths with applied bias has been investigated in a series of $In_xGa_{1-x}As$-GaAs MQW's. Good agreement between theory and experiment is found, but only by using a value for the piezoelectric constant $\sim 30\%$ smaller than the commonly accepted value. Strong lifetime broadening is observed close to flat band conditions in the well. This result contrasts strongly with that in nonpiezoelectric structures where the fields in the wells and barriers are equal, and lifetime broadening is observed at high fields in the wells.

We would like to thank G. Duggan for helpful discussions. This work was supported by SERC Grant No. GR/H20925.

---

*Permanent address: Departamento de Ingeniera Electronica, Universidad Politecnia de Madrid, Madrid, Spain.

[1]D. L. Smith, Solid State Commun. **57**, 919 (1986).

[2]C. Mailhiot and D. L. Smith, J. Vac. Sci. Technol. A **7**, 609 (1989).

[3]E. A. Caridi, T. Y. Chang, K. W. Goossen, and L. F. Eastman, Appl. Phys. Lett. **56**, 659 (1990).

[4]I. Sela, D. E. Watkins, B. K. Laurich, D. L. Smith, S. Subbanna, and H. Kroemer, Appl. Phys. Lett. **58**, 684 (1991).

[5]K. Nishi and T. Anan, J. Appl. Phys. **70**, 5004 (1991).

[6]G. Duggan, K. J. Moore, A. Raukema, G. Th. Jaarsma, and K. Woodbridge, Phys. Rev. B **45**, 4494 (1992).

[7]B. K. Laurich, K. Elcess, C. G. Fonstad, J. B. Beery, C. Mailhiot, and D. L. Smith, Phys. Rev. Lett. **62**, 649 (1989).

[8]*Semiconductors,* edited by O. Madelung, Landolt-Börnstein, New Series, Vol. 17 (Springer-Verlag, New York, 1982).

[9]The materials were processed into 400-$\mu$m-diameter annular diodes with 200-$\mu$m optical access (Ref. 12).

[10]A. S. Pabla, J. L. Sanchez-Rojas, J. Woodhead, R. Grey, J. P. R. David, G. J. Rees, G. Hill, M. A. Pate, P. N. Robson, R. A. Hogg, T. A. Fisher, A. R. K. Willcox, D. M. Whittaker, M. S. Skolnick, and D. J. Mowbray, Appl. Phys. Lett. **63**, 752 (1993).

[11]M. K. Saker, D. M. Whittaker, M. S. Skolnick, M. T. Emeny, and C. R. Whitehouse, Phys. Rev. B **43**, 4945 (1991).

[12]Shoulders are observed to higher energy on the PLE transitions, which are not observed in PC. These are attributed to small variatons in well width. The 2.3-meV separation between *E*1HH1 and its shoulder corresponds to a well width difference of $\sim 8$ Å.

[13]L. W. Molenkamp, R. Eppenga, G. W. 't Hooft, P. Dawson, C. T. Foxon, and K. J. Moore, Phys. Rev. B **38**, 4314 (1988).

[14]D. A. B. Miller, J. S. Weiner, and D. S. Chemla, IEEE J. Quantum Electron. **QE-22**, 1816 (1986).

[15]W. Chen and T. G. Andersson, Semicond. Sci. Technol. **7**, 828 (1992).

[16]E. Anastassakis, Phys. Rev. B **46**, 4744 (1992).

[17]R. People and S. K. Sputz, Phys. Rev. B **41**, 8431 (1990).

[18]For example, a 10-Å change in well width, the maximum variation from the TEM measurement, would lead to a 6-meV shift in the transition energy; a 1% change in $x$ changes the transition energy by 9 meV.

[19]The relatively low value of $E_p = 155$ kV/cm corresponding to $e_{14} = 0.097$ C/m$^2$ could also arise if the strain in the structures were relaxed by 30% (the reduction of $E_p$ from 227 to 155 kV/cm). However, such large strain relaxation would lead to a downshift of the *E*1HH1 transition energy by 26 meV, leading to predicted energies for $x = 0.15$ in strong disagreement with experiment.