# ELECTRIC FIELD EFFECTS ON INTERSUBBAND TRANSITIONS IN QUANTUM WELL STRUCTURES

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We report on a Raman scattering study of the electric-field dependence of $c_0 \rightarrow c_1$ intersubband transitions of photoexcited electrons in a 264 Å GaAs- $Al_{0.3}Ga_{0.7}As$ quantum-well structure. The measured Stark shifts are in very good agreement with theoretical predictions. The intensity of the intersubband peak increases rapidly with applied field due to parity-mixing. In contrast to the enhanced broadening shown by exciton resonances, the width of $c_0 \rightarrow c_1$ is nearly independent of the field. This feature is attributed to effects of structural disorder.

Recently, studies of the effect of electric fields perpendicular to the layers on the electronic properties of quantum-well structures (QWS's) have attracted much attention.[1-19] The interest is motivated in part by device applications (e.g., high-speed optical modulators)[2,8,10] which are based on the pronounced shifts of heavy-hole exciton resonances induced by the field. Experimentally, the excitonic Stark effect has been investigated in GaAs-$Al_xGa_{1-x}As$ QWS's by use of optical absorption,[3,9,10] photocurrent,[13,14], excitation spectroscopy[17], and photoluminescence[4,5,7,12,15] (PL) techniques. In addition, Stark shifts of intersubband transitions have been studied using far infrared absorption.[19] In this work, we report on a Raman scattering (RS) investigation of the electric-field dependence of $c_0 \rightarrow c_1$ intersubband transitions of photoexcited electrons [$c_0(c_1)$ denotes the lowest (first-excited) well state associated with the conduction band]. Stark shifts derived from our measurements are in very good agreement with theoretical calculations. The $c_0 \rightarrow c_1$ Raman peak shows an increase in intensity with applied field due to broken inversion symmetry, and a nearly field-independent width. The latter finding differs from the behavior shown by exciton resonances exhibiting field-enhanced broadening.[8,12,13] Disorder originated in structural defects is shown to account for this difference.

The sample used in our experiments was grown by molecular beam epitaxy on a Si-doped (001) GaAs substrate in the following sequence: 0.3-μm Si-doped ($n=2\times10^{18}cm^{-3}$) GaAs buffer layer, 0.19-μm $Al_{0.3}Ga_{0.7}As$, thirty uncoupled GaAs wells with thickness L=264Å (198-Å-thick $Al_{0.3}Ga_{0.7}As$ barriers), and 0.19μm $Al_{0.3}Ga_{0.7}As$ clad layer; unless indicated, the layers are nominally undoped. A semitransparent Schottky contact was formed by evaporating Au to build a 150-Å-thick film on top of the sample. Raman scattering measurements were performed at T=2K using a CW LDS698 (pyridin 1) dye laser, pumped by an $Ar^+$ laser. The laser beam was focused to a spot 200μm in radious; powers were in the range 0.1-0.15W. The estimated power density at the interface between the QWS and the clad layer is $P\approx6-10Wcm^{-2}$; these values are inferred from a determination of the reflectivity of the coated sample (≅70%) and the scattering intensity on and off the electrode. Raman spectra were recorded in the $z(x',x')\bar{z}$ and $z(x',y')\bar{z}$ backscattering configurations where z is normal to the layers and x', y' are along [110] and [1$\bar{1}$0] directions.

Figure 1 shows RS data of the QWS for different external d.c. voltages $V_{ext}$. The peak at 18.9meV ($V_{ext}=0$) is due

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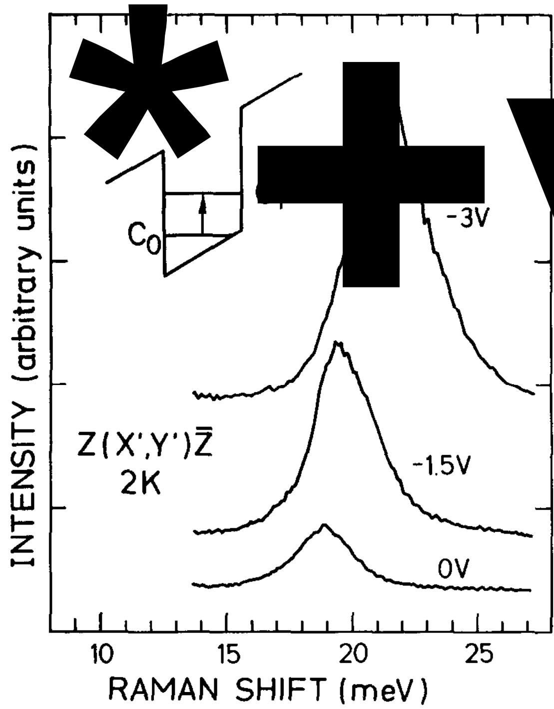


Fig. 1: Raman spectra of the 264-Å GaAs-$Al_{0.3}Ga_{0.7}As$ QWS showing the $c_0 \to c_1$ intersubband transition at different external voltages. The laser energy is $\omega_L$=1.685eV. *Counting rates at the maxima are* typically ~ 400 c $s^{-1}$ $W^{-1}$. The inset shows a schematic energy diagram (not to scale).

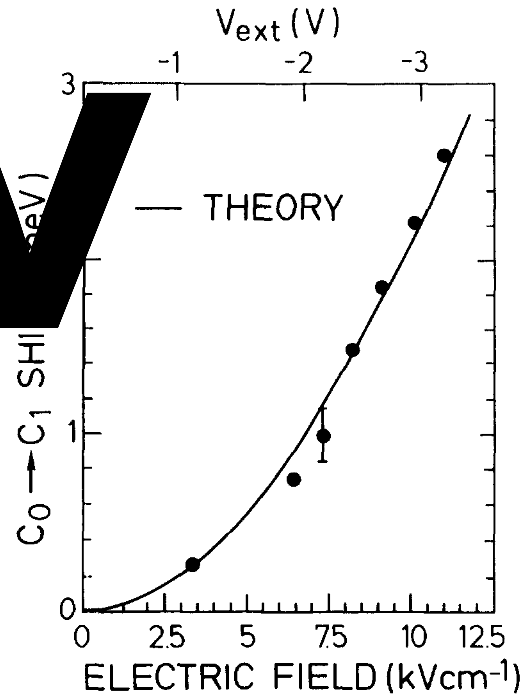


Fig. 2: Comparison between measured (full circles) and calculated $c_0 \to c_1$ Stark shifts.

to $c_0 \to c_1$ intersubband transitions of electrons. A calculation using the band-gap discontinuities determined by Miller et al.[20] predicts $c_0 \to c_1$=18.4meV. In the range of $V_{ext}$'s investigated, $-3V \leq V_{ext} \leq 0.9V$, *the FWHM (full-width at half maximum)* of $c_0 \to c_1$ remained nearly constant at ≈3meV. With increasing $|V_{ext}|$, the intersubband peak growths in intensity and shifts to higher energies, except for $0 \leq V_{ext} \leq 0.2V$. Since the shift and intensity must be even functions of *the electric field, it follows that* -0.2V is the built-in voltage of the structure.

The observation of the $c_0 \to c_1$ transition indicates that the lowest subband in the sample is partially occupied. This is due to photoexcitation[21], as revealed by results *on the P-dependence* of the scattering (not shown). A crude estimate based on parameters from the literature[7] gives a steady-state electron concentration $\sigma \sim 2\times10^9 cm^{-2}$ ($P=10Wcm^{-2}$). σ can also *be determined from the positions of the* intersubband peak in the (x',x') and (x',y') configurations.[22] The bare transition energy is given by the latter, while (x',x') exhibits a shift proportional to σ due to depolarization effects.[22] Our data reveal no appreciable shifts *(<0.25meV) which implies* $\sigma < 5\times10^9 cm^{-2}$. This upper limit is consistent with the estimate above.

In the range of fields studied (see below), the electron-hole recombination time does not vary enough[7,15] as to explain the increase in intensity shown by $c_0 \to c_1$ *(which might be attributed to a* larger steady-state population). At zero field, $c_0 \to c_1$ is strictly forbidden in RS because the states have different parities.[22] This indicates that the scattering enhancement results from parity-mixing due to the field as in field-induced absorption by forbidden excitons.[10]

The $V_{ext}$-dependence of the shift of $c_0 \to c_1$ is shown in Fig. 2, together with results of calculations. Theory and experiment are in very good agreement if a length of 2.7μm is used to convert voltages into fields. In the calculations, the eigenenergies of quasibound electron states were obtained numerically. We used the procedure described in Ref. 11 to avoid imaginary corrections to the energy due to tunneling, which are negligible in our case.

The observaton of a nearly field-independent width of $c_0 \to c_1$ is a significant feature of our results. This behavior differs significantly from the reported[8,12,13] field-induced enhanced broadening of exciton resonances which is mainly determined by interface roughness and inter-well size fluctuations[12] (tunneling effects are relatively unimportant in most cases studied[2-5,7-10,12-15] except at very high fields; they are vanishingly small in our structure). Structural defects lead to a clear differentiation between the field-dependent widths of excitons and intersubband transitions. The argument is simple; broadening due to fluctuations in the average well-width L and also due to island-roughness under conditions of localization[23] is approximately given by

$$\Gamma(E) = \frac{\partial \Omega(E)}{\partial L} \delta L \quad , \qquad (1)$$

where E is the field and Ω is the energy of the corresponding excitation. For excitons[11,12] Γ increases with E while it decreases for intersubband transitions. Calculations using the parameters of our structure and δL=2.83Å (one monolayer) give Γ=0.4meV (E=0) and Γ=0.3meV (E=12 kVcm$^{-1}$). Since δL does not commonly exceed 3-4 monolayers,[23] it is clear that other mechanisms (such as impurity scattering) contribute to the $c_0 \to c_1$ width.

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