Field-dependent linewidths and photoluminescence energies in GaAs-AlGaAs multiquantum well modulators

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Photoluminescence linewidths and transition energies have been measured in GaAs-AlGaAs multiple quantum wells with large ($\geqslant 160$ Å) barrier widths as a function of applied transverse electric field. The experimental data agree well with values calculated by using a recently developed variational technique. It is apparent that heterointerface roughness is the dominant line broadening mechanism. The emission intensity decreases rapidly with field, principally due to carrier tunneling at high fields. At 80 kV/cm a shift of 20 meV in the emission energy is observed.

High-performance modulation and switching devices are essential components in present-day communication systems. Modulation schemes using single and multilayered III-V compounds have been demonstrated.[1-3] More recently an interesting modulation principle, based on the quantum-confined Stark effect has been demonstrated by Wood *et al.*[4,5] Due to enhanced electroabsorption as a result of an electric field applied transversely across a multiquantum well (MQW) system, the excitonic absorption spectra shift in spectral energy as a function of the field strength. A large modulation of the transmitted signal can therefore be obtained. In the study being reported in this letter, we have theoretically and experimentally investigated the photoluminescence (PL) spectra in GaAs-AlGaAs uncoupled finite quantum well systems as a function of an electric field applied transversely across the devices. In particular, the PL linewidth, peak energy, and intensity dependence on field have been analyzed.

The modulation action of single and multiquantum wells in the presence of an electric field is dependent upon one or more of the following physical phenomena: (i) shift of the electron and hole subband energies in the quantum well, (ii) change in the overlap of the electron and hole wave functions in the quantum well, and (iii) the tunneling of electrons and holes out of the quantum well. These three effects are primarily responsible for the change in emission and/or absorption wavelength and change in intensity of emission or absorption of light as a function of electric field. In addition, the full width at half-maximum (FWHM) of the emission (absorption) peak is also critical if significant modulation is to be achieved. Efficient modulation will not be realized if the FWHM is larger than the energy shift of the excitonic energy. A dominant broadening effect in narrow quantum wells is due to interface imperfections. In this letter we present theoretical and experimental results on the above-mentioned aspects of optical properties of quantum wells.

The potential of a square quantum well may be defined by

$$\begin{aligned} V(x) &= 0, \quad \text{if} \quad x_0 \leqslant x \leqslant x_0 + w \\ &= V_0, \quad \text{if} \quad x < x_0 \quad \text{or} \quad x > x_0 + w, \end{aligned} \tag{1}$$

where w is the well size and V_0 is the energy barrier. In the presence of an electric field an additional potential is superimposed on the above potential:

$$\widetilde{V}(x) = eEx. \tag{2}$$

In the presence of electric field, the electron and hole subband levels are quasi-bound states which will eventually tunnel out of the quantum well region. The quasi-bound exciton in the well has an energy ε_{ex} given by

$$\varepsilon_{\text{ex}}(E) = \varepsilon_{\text{ph}}(E) = \varepsilon_e(E) - \varepsilon_h(E) + \varepsilon_g(E) - \varepsilon_b(E), \tag{3}$$

where ε_e, ε_h, ε_g and ε_b are, respectively, the electron subband level, hole subband level, band gap, and exciton binding energy, respectively. ε_{ph} is the photon energy corresponding to the creation or annihilation of the exciton. The dominant contribution to the exciton energy shift with electric field arises from the shift of ε_e and ε_h. ε_g is not affected at the electric fields used and changes in ε_b, estimated from the variation of the electron-hole overlap integral

$$M_{\text{eh}} = \int \psi_e^* \psi_h \, dz \tag{4}$$

are about an order of magnitude lower than the changes of the electron and hole subband level positions at the highest fields used in the experiments. In addition, we note that the FWHM of the excitonic transition is given by[6]

$$\sigma(E) = \alpha \frac{\partial \varepsilon_{\text{ex}}(E)}{\partial W} \delta W, \tag{5}$$

where δW is the interface roughness in the growth direction and α is a constant (<1) dependent upon the lateral extent of the two-dimensional islands describing interface roughness. When the extent of the islands approaches the exciton radius, α tends to unity. α can be estimated by fitting the zero-field excitonic linewidths.

We have used a variational approach based on the Monte Carlo method[7] to solve Eqs. (1)–(5). This allows us to determine the electron and hole subband levels, the overlap integral M_{eh}, and the electron and hole tunneling rates as a function of electric field. We have also calculated $\partial \varepsilon_{\text{ex}} / \partial W$ as a function of electric field. The calculations have been done assuming a 85:15 and 60:40 band offset for the conduc-

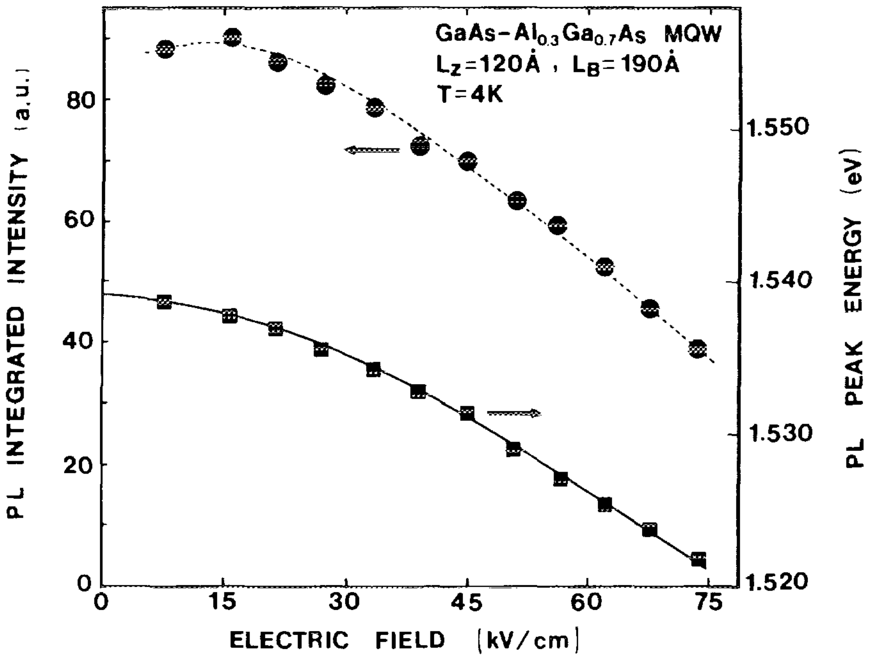

FIG. 1. Measured variations of photoluminescence intensity and peak energy with applied transverse electric field. The solid line represents calculated values of the emission energy and the dotted line is a join of the experimental data points.

tion and valence bands of GaAs and AlGaAs. We find that while the electron and hole tunneling rates are extremely sensitive to the band offset distribution, the energy positions and linewidths are relatively insensitive at all electric fields.

GaAs-Al$_{0.3}$Ga$_{0.7}$As quantum well structures were grown by molecular beam epitaxy (MBE) on suitably doped GaAs substrates. Details of growth and substrate preparation have been mentioned in an earlier publication.[8] Typical parameters of the quantum wells studies are $L_z = 90$–120 Å, $L_B = 160$–200 Å, and 30 periods. Semitransparent Au films were evaporated on the top surfaces to form Schottky diodes. Typical reverse breakdown voltages in these devices varied from 5 to 10 V.

Field-dependent photoluminescence measurements were done at 4 K on samples mounted in a strain-free manner with a tunable dye laser (759.4 nm) as the excitation source. The luminescence was collected and analyzed with a 1.26-m double-pass Spex spectrometer. Measurements were made with various biases applied to the devices. The photoluminescence spectra are characterized by a single excitonic peak which is composed of free and bound exciton transitions.

Figure 1 shows the measured variation of the peak energy position and change of the integrated PL intensity of the main peak with electric field. The increase in linewidth with applied bias is depicted in Fig. 2. The data shown in Figs. 1 and 2 are for a sample in which the quantum wells are characterized by $L_B = 190$ Å and $L_z = 120$ Å. It should be mentioned here that due to uncertainties in the materials and device parameters, an exact value of the applied field could not be determined accurately. Therefore, the field was computed from the variation of peak energy with field at a single value. Using this as a calibration value the variation over the entire field range agreed well with the theoretically computed variation.

The solid lines in Figs. 1 and 2 represent the results of calculations for a band-edge discontinuity of 60:40. There is no significant change in the emission energy dependence of electric field if a 85:15 discontinuity is used. Clearly, the assumed band discontinuity does not have any significant effect. We should point out that a two-monolayer interface roughness over the entire MQW structure is able to explain the line broadening data quite well. We believe that the scatter in the measured linewidths is partly due to the large asymmetry of the emission line shape in the lower energy side. Weiner *et al.*[9] have recently suggested that the line broadening may be due to change in exciton lifetimes in presence of the electric field. However, we find that although qualitatively this is true, quantitative agreement is obtained if one regards interface roughness as the dominant broadening mechanism. The decrease in the PL intensity of the excitonic peak is due to the tunneling of the electrons and holes out of the quantum well. However, since the incident light in our experiment has an energy ~100 meV above the exciton

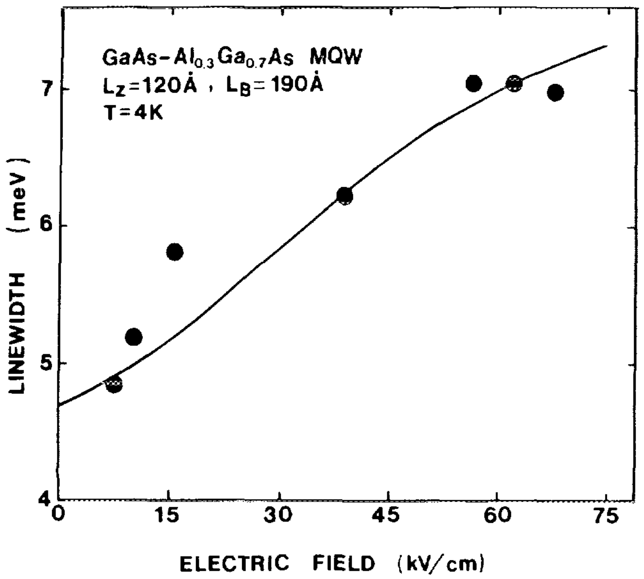

FIG. 2. Calculated (solid line) and measured photoluminescence linewidths (FWHM) as a function of transverse electric fields.

energy, electron and holes can tunnel out before they form the excitons. The calculated PL intensity dependence on electric field does not quantitatively agree with the experimental data for the above-mentioned reason. Further work is in progress to obtain the intensity dependence with resonant photoexcitation since valuable information about the band-edge discontinuity can then be obtained.[10]

From the data of Fig. 1 it is evident that fairly large modulation depths can be realized. More important, the quenching of photoluminescence at high fields is determined primarily by tunneling rates of electrons and holes.[7] The tunneling time constants are ~ *ps* and can be tailored by varying the quantum well parameters. Using these tunneling rates, a high-speed modulator working in the emission mode can be realized. Though the intensity of the modulated beam will be low, there can be advantages. The device can be photo excited laterally and can therefore be monolithically integrated with sources and detectors having the same multiquantum wells in the active region. More important, since the luminescence is not directed, an array of detectors can be monolithically integrated on the same chip to enable parallel processing.

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