EXCITONIC TRANSITIONS AND OPTICALLY EXCITED TRANSPORT IN $GaAs/Al_xGa_{1-x}As$ QUANTUM WELLS IN AN ELECTRIC FIELD

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The effects of electric fields on excitons in $GaAs/Al_xGa_{1-x}As$ quantum wells have been studied using the technique of photocurrent spectroscopy. The quantum wells were imbedded in the depletion region of p-i-n and Schottky barrier photodiodes. A sequence of distinct exciton absorption peaks are seen in the photocurrent spectra for the diodes. Biasing the diodes allows the electric field in the quantum well to be varied. Stark shifts of the excitons were observed in the applied field. For a given field and well width the lowest energy heavy hole (h_1) and light hole (l_1) excitons exhibited the largest shifts. Some of the higher energy excitons exhibited extremely small shifts. Unallowed exciton peaks became visible in the photocurrent spectra as the electric field was increased. One of these peaks was only visible for wells with widths greater than approximately 120 Å and was shown to arise from mixing between the heavy and light hole valence band subbands. Negative differential resistance regions were observed in the optically excited current-voltage curves for the photodiodes. These were a result of the Stark shifts of h_1 and l_1.

The effects of electric fields on excitonic transitions between valence and conduction band subbands in semiconductor superlattices and quantum wells have recently received considerable attention. Most of these studies have concentrated on the electronic properties of the lowest energy heavy hole h_1 and light hole l_1 excitons. These excitons involve transitions between the $n=1$ conduction band subband and the $n=1$ heavy and light hole valence band subbands, respectively (see for example Ref. 1-3). We have made a photocurrent study of the effects of electric fields on h_1 and l_1 and on the higher energy excitons in $GaAs/Al_xGa_{1-x}As$ quantum wells, where the higher energy excitons are optical transitions between conduction and valence subbands for which $n>1$. In this study the quantum wells were imbedded in the depletion region of $GaAs/Al_xGa_{1-x}As$ photodiodes, and fields were applied by biasing the diodes. We have made a comparison of the effects of electric fields on the various excitons, and have also studied the transport perpendicular to the wells of the carriers which have been optically excited into the quantum well subbands. Here we present a summary of this work.

The samples used in this study were grown by molecular beam epitaxy (MBE). An n^+ buffer layer of GaAs was grown on an n^+ GaAs substrate. An undoped layer of $Al_xGa_{1-x}As$ was grown on top of the buffer layer. Quantum wells were imbedded in the $Al_xGa_{1-x}As$ layers. A final thin p^+ layer of GaAs was grown on top of the $Al_xGa_{1-x}As$ or a thin metal Schottky barrier was evaporated onto the $Al_xGa_{1-x}As$ to form a p-i-n or Schottky barrier photodiode. The samples were mounted in a variable temperature cryostat and illuminated with light from a grating monochromator. The photocurrent passing through the samples was recorded as a function of illumination wavelength to obtain photocurrent

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spectra. In addition, current-voltage (I-V) curves for the diodes were recorded for a fixed illumination wavelength.

Fig. 1a presents photocurrent spectra at two different biases for a diode in which the intrinsic region was composed of 10 quantum wells. The wells were approximately 80 Å wide and the barriers were approximately 100 Å wide. The spectra strongly resemble absorption spectra for quantum wells.[4] At low electric fields (0.5 V) only h_1 and l_1 are visible. As the electric field is increased (-3.0 V), additional excitonic peaks become visible. These correspond to transitions between valence and conduction subbands for which $\Delta n \neq 0$. Such transitions are forbidden in square quantum wells. They become visible when an electric field is present due to the polarization of the subband wavefunctions in the field which leads to an increase in the optical matrix element for transitions between subbands. This polarization is predicted to cause a decrease in the absorption coefficient for allowed transitions such as h_1 and l_1.[5] The h_1, l_1 and h_{12} (n=1 conduction subband and n=2 heavy hole valence subband) excitons have been labelled in Fig. 1a. Stark shifts of these excitons can be seen in Fig. 1a. The peaks move to longer wavelengths when the reverse bias voltage is increased. The Stark shifts of these three peaks are presented in more detail in Fig. 1b. The shift in the h_{12} peak is clearly smaller than that of h_1 and l_1. This is due to a reduced shift in the n=2 heavy hole valence subband toward the GaAs valence band edge in comparison to the n=1 heavy and light hole subbands. Qualitatively, this difference follows from a second order perturbation theory analysis of the Stark shift of energy levels in a one-dimensional quantum well.[2] The solid lines in Fig. 1b are calculated shifts using the envelope function approximation. It was in general found that the Stark shifts of the higher energy excitons were less than that of h_1 or l_1. These results are discussed in more detail in Ref. 6. In samples with well widths larger than approximately 120 Å, as the electric field was increased, two peaks became visible in the energy range where only h_{12} was expected to occur. Polarization and uniaxial stress dependent photocurrent spectra revealed that one of the states was the result of mixing between the first light hole and second heavy hole valence band subbands.[7] The observation of this mixed state is extremely significant since it is the strongest evidence to date of valence band mixing in quantum wells.

The transport of optically excited carriers through the depletion region of the photodiodes was also studied. When the temperature was greater than approximately 120 K, the photocurrent at a given voltage and position in the photocurrent spectrum was thermally activated. Below 100 K the temperature dependence of the photocurrent varied from sample to sample. Samples in which the depletion region was composed of quantum wells separated by 100 Å barriers (such as the sample in Fig. 1a) actually

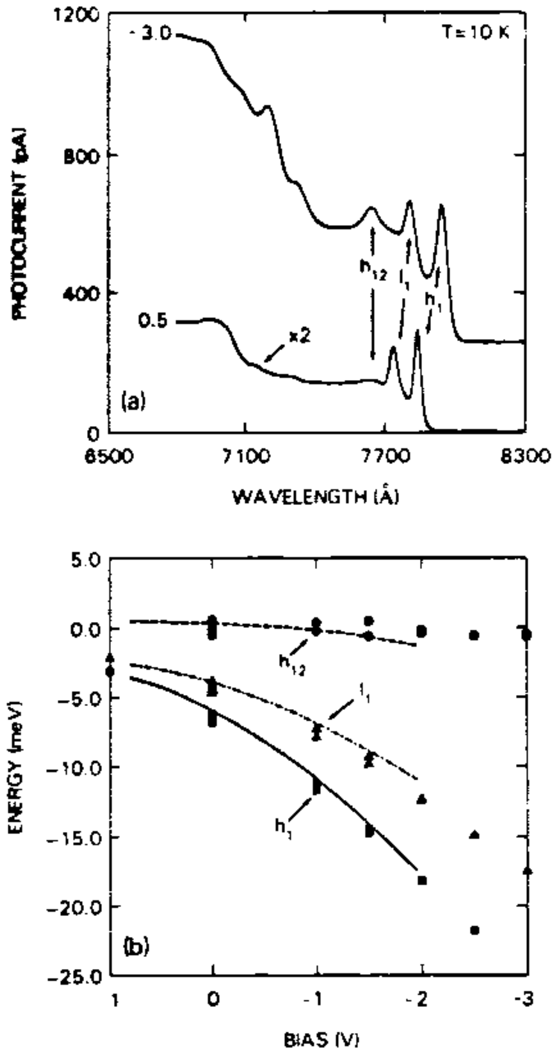

Fig. 1: a.) Photocurrent spectra at two different bias voltages for a p-i-n photodiode with an intrinsic region composed of 10 AlAs/GaAs quantum wells. Forward bias is positive. Well widths were 80 Å. Barrier widths were 100 Å. The three lowest energy exciton peaks have been labelled. In samples with wider wells, two peaks are visible in the energy range where only the h_{12} peak is expected to be seen. The baselines for the spectra have been offset for clarity. Measurements were made at 10 K. b.) Stark shifts of the exciton peaks as a function of bias voltage. The solid lines are calculated energies assuming a 2450 Å intrinsic region width.

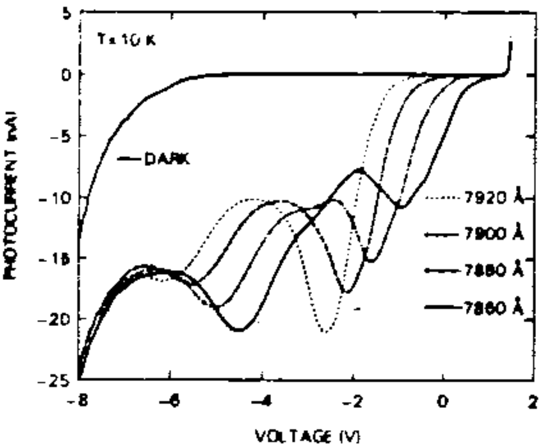

Fig. 2 Reverse bias current-voltage characteristics with and without optical excitation for the sample from which the data in Fig. 1 was obtained. Negative differential resistance regions due to the Stark shifts of the h_1 and l_1 excitons are visible in the curves. Measurements were made at 10 K.

exhibited an increase in photocurrent with decreasing temperature. This behavior was not entirely understood, but, since tunneling is the most likely transport mechanism for these samples in this temperature range, it may have been due to a reduction in acoustic phonon scattering of the carriers as they tunneled. In the rest of the samples where the barriers were wider, the photocurrent continued to decrease as the temperature was reduced below 100 K. The low temperature I-V characteristics of the photodiodes under optical excitation at wavelengths close to h_1 and l_1 exhibited wavelength dependent negative differential resistance regions. Fig. 2 illustrates this for the sample from which the spectra in Fig. 1a were obtained. The negative differential resistances visible in Fig. 2 are due to the Stark shifts of the h_1 and l_1 exciton energies through the energy of the excitation source. Additional wavelength independent structure was present in the optically excited I-V characteristics of this sample. This structure is probably due to an increase in the transmission probability through the barriers at energies where valence band subbands in adjacent wells align. Photoexcited transport in the photodiodes is discussed more thoroughly in Ref. 8.

To summarize, we find the Stark shifts of higher energy excitons in quantum wells are generally smaller than that of the lowest energy heavy (h_1) and light (l_1) hole excitons. The oscillator strengths for forbidden transitions in quantum wells increase as the electric field in the well is increased. In addition, an exciton peak arising from mixing between the valence band subbands also became visible as the field was increased. Finally, wavelength dependent negative differential resistance regions and wavelength independent structure were both visible in the optically excited I-V characteristics of the photodiodes as a result of the quantum wells present in the intrinsic region.

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