# Brief Reports

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## Binding energies of biexcitons in $Al_xGa_{1-x}As/GaAs$ multiple quantum wells

D. C. Reynolds, K. K. Bajaj,* C. E. Stutz, and R. L. Jones
*Electronic Technology Laboratory (AFWAL/ELR), U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio 45433*

W. M. Theis and P. W. Yu
*University Research Center, Wright State University, Dayton, Ohio 45435*

K. R. Evans
*Universal Energy Systems, 4401 Dayton-Xenia Road, Dayton, Ohio 45324*
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We report observations of transitions associated with biexcitons in $Al_xGa_{1-x}As/GaAs$ multiple-quantum-well structures of well widths from 200 to 350 Å, using resonant excitation and photoluminescence spectroscopies. The observed biexciton binding energies agree well with those calculated by Kleinman [Phys. Rev. B **28**, 871 (1983)]. In contrast, earlier measurements by Miller *et al.* [Phys. Rev. B **25**, 6545 (1982)] gave biexciton binding energies which agreed with Kleinman's results for well sizes below 150 Å but were significantly greater for larger well sizes. In addition, we report on the biexciton emission-strength dependence on pump power, temperature, and applied-magnetic-field strength.

The existence of biexcitons in $Al_xGa_{1-x}As/GaAs$ quantum wells was first suggested by Miller *et al.*,[1] who observed a double peak in the photoluminescence (PL) spectra of several high-quality multiple-quantum-well (MQW) samples of differing well sizes. Based upon polarization, temperature, and excitation-intensity dependencies, they tentatively assigned the lower-energy peak to a transition involving the two-dimensional biexciton ($XX$). However, their calculated $XX$ binding energy ($E_{XX}$) obtained by using a two-parameter variational wave function fell below their measured values for all well sizes investigated. Later Kleinman,[2] using the six-parameter variational wave function of Brinkman *et al.*,[3] calculated $E_{XX}$ values and found them to be about 70% greater than those obtained by Miller *et al.*[1] These new calculated values were in much better agreement with the measured values for well sizes below about 150 Å. However, the measured $E_{XX}$ values were significantly greater than the theoretically predicted values for well sizes above 150 Å. No explanation for this discrepancy was given. Recently, Charbonneau *et al.*[4] reported on the observation of $XX$ in a 142-Å $Al_xGa_{1-x}As/GaAs$ MQW with $E_{XX}=1.25$ meV.

In this Brief Report, we report on the observation of biexcitons in $Al_xGa_{1-x}As/GaAs$ MQW's of nominal 200–350 Å well widths. In contrast to the previous measurement,[1] the observed $E_{XX}$ in this study agree well with the theoretically predicted values[2] for all well sizes investigated. At an ideal excitation intensity for the formation of $XX$, we observe that the biexciton emission signal decreases when a magnetic field is applied or when the sample temperature is increased.

For PL measurements, an $Ar^+$-ion laser was used for excitation while resonant-excitation (RE) measurements used an $Ar^+$-ion-laser–pumped-dye-laser (Styryl-9 dye) for excitation. At low excitation intensities ($\leq 50$ mW/cm$^2$) the RE method gave rise to $XX$ emission signals of much greater strength than those obtained in PL. Emission of the sample immersed in liquid He at 2 K was monitored by a 4-m spectrometer capable of a dispersion of 0.54 Å/mm in this spectral region and equipped with a RCA C31034A photomultiplier tube.

The nonintentionally doped MQW's investigated were grown by molecular-beam epitaxy using a Varian Gen II. Each MQW structure contained 30 or 40 repeats of a given well size and was grown on a GaAs buffer layer with an underlying 10-cycle $Al_{0.25}Ga_{0.75}As/GaAs$ (30 Å)/(30 Å) superlattice for impurity trapping and surface

 

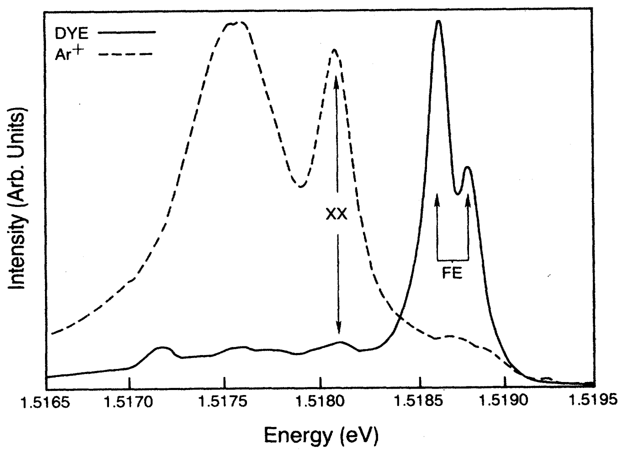


FIG. 1. PL (excitation by $Ar^+$ laser at 1250 $mW/cm^2$) and RE (dye laser tuned to $n=2$ of HHFE at 50 $mW/cm^2$) for nominal 300 Å well size.

smoothing. The wells varied in size from 200 to 350 Å with 100-Å $Al_{0.25}Ga_{0.75}As$/GaAs barriers. The structures were grown using $As_2$ on $n^+$-type or $p^+$-type GaAs substrates oriented 6° off [100] toward [111]$A$. The GaAs growth rate was 0.5 monolayers/sec; the growth temperature was approximately 620 °C and was adjusted to yield a barely arsenic-rich surface reconstruction.

Enhancement of $XX$ emission in RE at low excitation intensities is believed to be due to increased probability for binding of pairs of excitons which have the same kinetic energy. This occurs in RE since the excitons are created with essentially zero kinetic energy, thereby enhancing $XX$ formation. Consequently, no $XX$ emission is observed in PL for 150 $mW/cm^2$ excitation intensity, while it is observed in RE using 12 $mW/cm^2$ excitation intensity. Figure 1 compares RE and PL for a nominal 300-Å MQW at 50 and 1250 $mW/cm^2$ pump power, respectively. When the excitation intensity is increased, the superlinear growth of the $XX$ emission is observed. The RE intensity could not be increased above 50 $mW/cm^2$ since that was the maximum output of our dye laser. The high-energy peaks at 1.518 79 and 1.518 64 eV are the heavy-hole free-exciton (HHFE) transitions separated in energy corresponding to a one monolayer variation in well size. These features dominate RE and are also observed in PL. The peak marked $XX$ is assigned to the biexciton transition. The pump-power densities for the dye and $Ar^+$ lasers are measured at laser output but are reduced approximately by half at the crystal due to the Dewar and Cryogen. Due to the higher intensity of the $Ar^+$ exciting source for the PL compared to that used for RE, the intensity of $XX$ emission reflects the increased exciting intensity of the $Ar^+$ exciting source.

Varying the excitation intensity of the $Ar^+$-ion laser, we observe a power relationship in PL between the peak

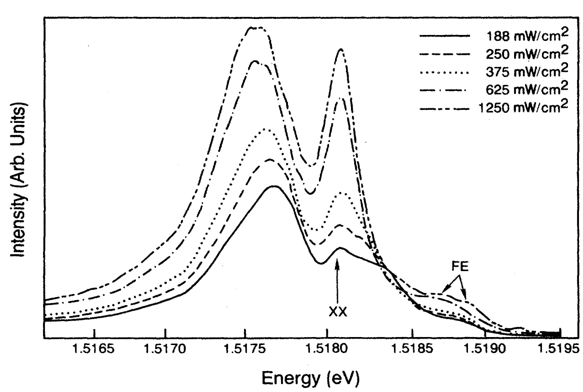


FIG. 2. Pump-power dependence of PL for 300-Å quantum well. Each PL spectrum has been scaled and, therefore, cannot be directly compared.

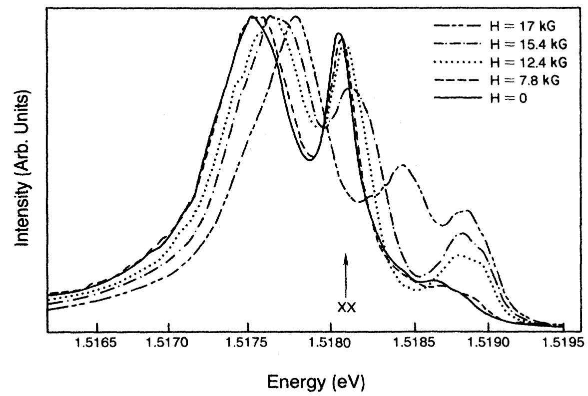


FIG. 3. Magnetic field dependence of PL for 300-Å quantum well at 1250 $mW/cm^2$.

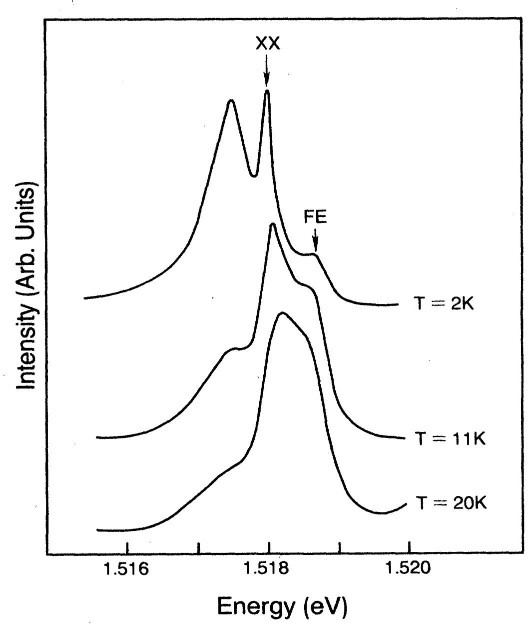


FIG. 4. Temperature dependence of PL for 300-Å quantum well at 1250 $mW/cm^2$.

emission intensity $I_{XX}$ of the biexciton and the intensity $I_{FE}$ of the free exciton [$A_{XX} \approx (I_{FE})^Y$], where $Y$ is found to be 1.7 without taking into account the different line shapes. Therefore, the measured value of 1.7 indicates the presence of superlinearity, but it should not be taken as a precise value. Variation of $I_{XX}$ as a function of $Ar^+$ laser excitation from 187 to 1250 mW/cm$^2$ is shown in Fig. 2 and is seen to be superlinear, as is expected for $XX$ formation.

When a magnetic field is applied to this same sample, the $XX$ transition intensity decreases. The magnetic field is applied parallel to the grown layers and is increased from 7.8 to 24 kG with resultant PL emission shown in Fig. 3 for an excitation intensity of 1250 mW/cm$^2$. The effect of the field is to compress the excitonic wave functions, reducing the interaction between excitons so that $XX$ formation is reduced. The temperature dependence of PL emission intensity is shown in Fig. 4. The rapid decrease of the ratio of $XX$ to $X$ demonstrates the expected sharp temperature dependence of the $XX$ transition due to the small $XX$ binding energy. At 30 K, the light-hole free exciton (LHFE) is observed on the high-energy side of the HHFE since the light-hole valence band is expected to have a significant thermal population at this temperature.

Agreement of the observed $E_{XX}$ (dots in Fig. 5) versus well size with the calculated values[2] (solid line) is considerably better than previously observed[1] $E_{XX}$ (▲'s in Fig. 5). $E_{XX}$ is shown versus HHFE position (lower scale) which is converted to well size (upper scale) by adding the confinement energy obtained in a finite–square-well calculation of electronic levels for the heavy hole and electron to the GaAs band gap and then subtracting the HHFE binding energy.[5] The calculated results of Kleinman[2] are then spline interpolated to this calculated well-size axis, yielding the solid curve shown.

In conclusion, the $E_{XX}$ observed in nominal 200–350 Å well widths are found to be in much better agreement

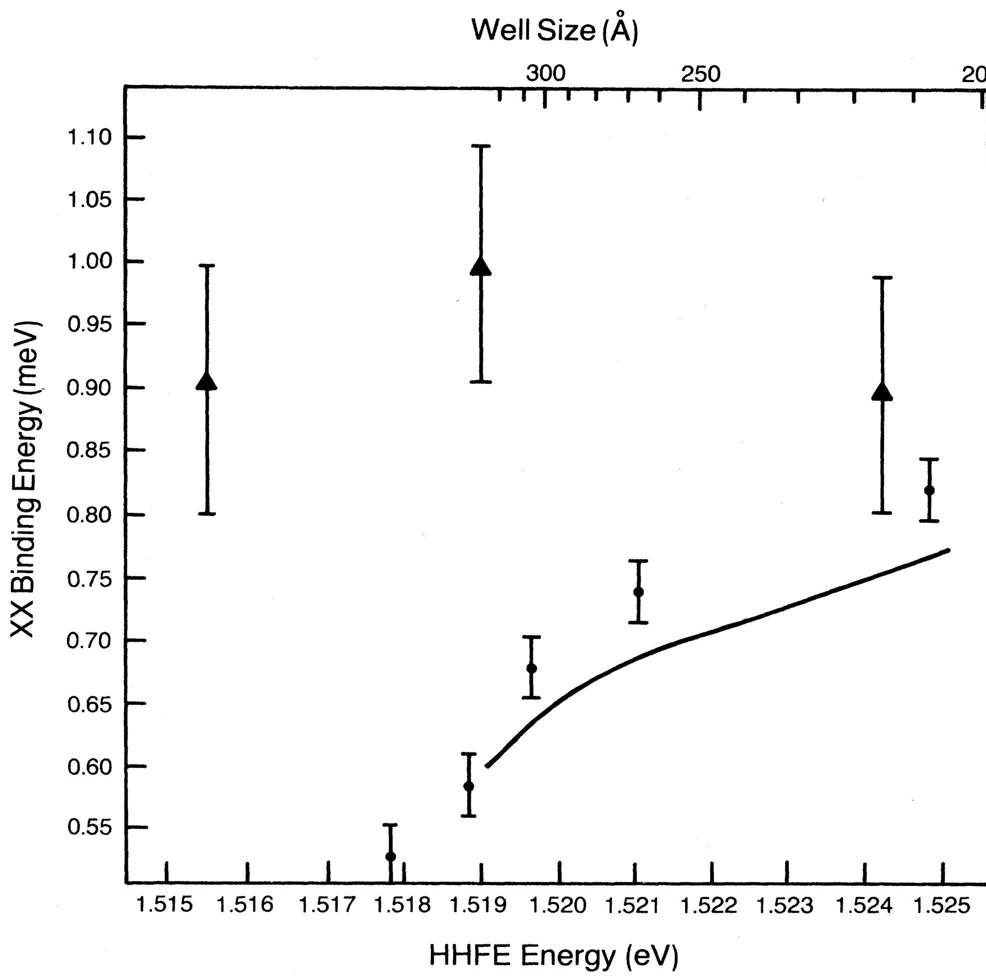


FIG. 5. Binding energy of $XX$ vs HHFE transition energy (lower scale) and calculated well width (upper scale). Theoretical values[2] are indicated by the solid line. The points shown as ▲'s were taken from Ref. 1; the points shown as dots are the present data.

with calculated values[2] than previous measurements.[1] A superlinear pump-power dependence of $I_{BE} \approx (I_{FE})^{Y}$ is observed as well as a temperature and magnetic field quenching of $XX$, thus confirming our identification.

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*Present address: Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-6206.

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