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Observation of free and bound excitons associated with the two-dimensional electron gas in modulation-doped heterostructures

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Overlapping bulk and two-dimensional excitons have been observed in modulation-doped heterostructures. Their differing behavior in a magnetic field allows them to be studied separately. Both free and bound excitons, associated with the two-dimensional electron gas, have been observed in the photoluminescence spectra of these structures. These excitons show a reduced binding energy due to screening and are found in a region of the structure where band-gap renormalization occurs due to many-body interactions. The two-dimensional excitons are identified from measurements conducted in applied magnetic fields.

I. INTRODUCTION

We report the results of photoluminescence (PL) measurements made on modulation-doped heterostructures both with and without applied magnetic fields. The emission spectra show distinctive features associated with a two-dimensional electron gas (2DEG).

Both free and bound two-dimensional excitons (X_{2D}) are observed in these modulation-doped single $Al_xGa_{1-x}As$-GaAs heterostructures. The two-dimensional exciton is defined as an exciton formed from an electron associated with the 2DEG and a valence-band hole. A magnetoexciton of similar nature was observed by Driessen, Olsthoorn, and Giling[1] in undoped heterostructures. In heterostructures of this type, bulk GaAs free and bound excitons, formed in the GaAs active layer, are superimposed with free and bound X_{2D}'s. The two types of excitons are identified by their different diamagnetic shifts. It would be expected that X_{2D} would have a smaller binding energy than the bulk GaAs free exciton (X) due to screening effects. This would result in a larger diamagnetic shift for X_{2D} than for X, which is clearly observed. With the smaller binding energy it would be expected that X_{2D} would come at a higher transition energy than X in zero magnetic field. The opposite is observed, and it is believed that renormalization of the band gap due to many-body interactions results in a smaller band gap in the notch region and thus a lower energy for X_{2D}. Band-gap lowering due to many-body interactions has been reported by Pinczuk *et al.*[2] in modulation-doped GaAs-$Al_xGa_{1-x}As$ quantum wells. From the diamagnetic shifts and the known binding energy of X (4.2 meV), the binding energy of X_{2D} was determined (3.4 meV). The quadratic relationship between the photon energy and the magnetic field allows one to determine the transition energy of X_{2D} at zero field by extrapolation. This analysis gives a band-gap lowering of approximately 2 meV resulting from many-body interactions.

The bulk GaAs neutral donor bound exciton (D^0,X) transitions and neutral acceptor bound exciton (A^0,X) transitions are also observed. These transitions have diamagnetic shifts comparable to those of X, as would be expected since the binding energies of the excitons to these centers is small. Transitions are observed on the low-energy side of D^0,X and A^0,X with diamagnetic shifts comparable to those of X_{2D}. These transitions we assign to D^0,X_{2D} and A^0,X_{2D}. The linewidths of these transitions are greater than the analogous transitions associated with bulk GaAs. This results from the increase in binding energy of the donors and acceptors as one moves from the notch region toward the neutral GaAs region due to decreased screening. The increased binding-energy results in an increase in the binding energy of X_{2D} to the center as described by Haynes.[3] As the transitions move from the notch region toward the neutral GaAs region, the binding energy will increase, resulting in a long-wavelength tail on the transition energy since the transition energy is the X_{2D} energy minus the binding energy of X_{2D} to the center. The energy, diamagnetic shift, and linewidth of these transitions are all consistent with the D^0,X_{2D} and A^0,X_{2D} assignments.

II. EXPERIMENTAL DETAILS

The sample studied was an $Al_xGa_{1-x}As$-GaAs heterostructure grown by molecular-beam epitaxy (MBE) on a semi-insulating GaAs substrate. The sample was nominally oriented 2° from (100) toward the nearest (110). A Perkin-Elmer cracker cell was used to produce dimeric arsenic as the arsenic growth species. The buffer-layer sequence consisted of 500-Å GaAs, followed by a ten-cycle [(30-Å $Al_xGa_{1-x}As$)/30-Å GaAs]) superlattice, followed by 5000-Å GaAs with an additional 200-Å Be-doped (10^{15} cm^{-3}) GaAs; this was followed by 20-Å undoped $Al_xGa_{1-x}As$ with an additional 400-Å uniformly doped (1×10^{18} cm^{-3}Si) $Al_xGa_{1-x}As$. The x value in all cases was 0.3. The structure was terminated with a 100-Å GaAs undoped cap. Hall-effect measurement were carried out at 77 K, and analyzed by a technique which makes use of the magnetic-field dependence of the conductivity and Hall coefficient in order to separate the two-dimensional electron gas (2DEG) characteristics from those of the doped $Al_xGa_{1-x}As$ layers.[4] The resulting mobility and carrier concentration were 4.15×10^4 $cm^2/V\,s$ and 1.07×10^{12} cm^{-2}, respectively (typical numbers for this type of structure). The knowledge of the 2D carrier concentration allows us to accurately model the band bending.

The PL spectra were excited with an Ar^+-ion laser-pumped tunable dye laser using Styryl 9 dye. The measurements were made at 2 K with the sample immersed in liquid He. The spectra were analyzed with a high-resolution 4-m spectrometer equipped with an RCAC31034A photomultiplier tube for detection.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In zero applied magnetic field all of the bulk GaAs exciton transitions are clearly observed (Fig. 1). Only one transition associated with X_{2D} is observed, that being A^0,X_{2D}. This observation, however, is significant in that it allows the experimental determination of the zero-field A^0,X_{2D} transition energy. The transition energies over the same spectral range in applied magnetic fields of 27.0, 28.2, and 30.0 kG are shown in Fig. 2. All of the transitions X; D^0,X; A^0,X; X_{2D}; D^0,X_{2D}; and A^0,X_{2D} are observed. X is observed to split in these magnetic fields; however, X; D^0;X; and A^0,X show only small diamagnetic shifts with these relatively small changes in magnetic fields. On the other hand, X_{2D}; D^0,X_{2D}; and A^0,X_{2D} show very detectable diamagnetic shifts which are characteristic of reduced binding energies. In Fig. 3 the diamagnetic shifts of all the transitions are plotted. The experimental points are plotted as □'s for the X transitions, and as 0's for the X_{2D} transitions. The quadratic relationship between the photon energy and the magnetic field permits the extrapolation of the X_{2D} transitions to zero applied field. The dashed lines are the extrapolated parts of the curves. It is noted that the extrapolated and measured zero-field transition energies of A^0,X_{2D} are very close. This gives confidence that the extrapolated zero-field transition energies of X_{2D} and D^0,X_{2D} are also very close. This gives confidence that the extrapolated zero-field transition energies of X_{2D} and D^0,X_{2D} are also very close to the real values. The similarities in the diamagnetic shifts of X; D^0,X; and A^0,X is clearly observed; also the diamagnetic shifts of X_{2D}; D^0,X_{2D}; and A^0,X_{2D} are very similar.

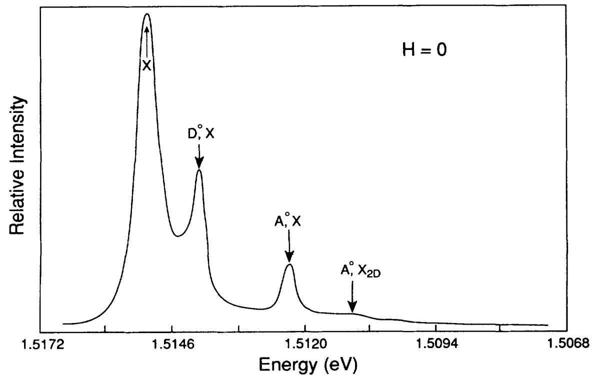

FIG. 1. Photoluminescence spectra showing the free and bound exciton transitions in bulk GaAs as well as the bound two-dimensional exciton transition A^0,X_{2D}.

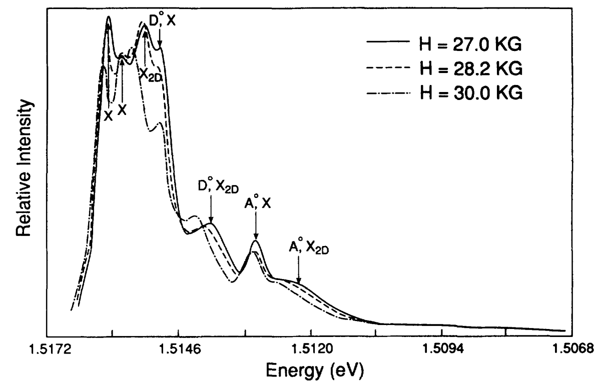

FIG. 2. Photoluminescence spectra showing the free and bound bulk exciton X as well as $2D$ exciton X_{2D} transitions in various applied magnetic fields.

The energies of the diamagnetic shifts can be estimated by the following expression:

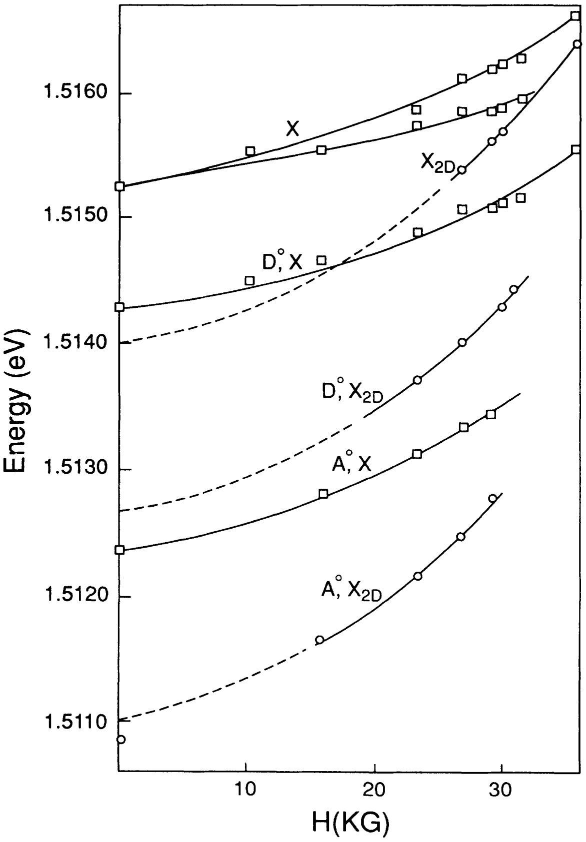

FIG. 3. The diamagnetic shifts for the free and bound X and X_{2D} transitions. For the X_{2D} transitions as well as the X transitions the solid lines are drawn through experimental points. The dashed lines for the X_{2D} transitions are extrapolated following a B^2 dependence. Note that the extrapolation for A^0,X_{2D} falls close to the measured zero-field point.

$$w=\frac{1}{2}\frac{e^2A}{4\pi mc^2}|B|^2 . \tag{1}$$

A is the orbital area of the exciton which is πa_0^2, where a_0 is the Bohr radius (proportional to m^{-1}). From the measured diamagnetic shifts and the known reduced mass m_X of X, the following relationship gives the reduced mass $m_{X_{2D}}$ of X_{2D}:

$$w_{X_{2D}} m_{X_{2D}}^3 = w_X m_X^3 . \tag{2}$$

A reduced mass $m_{X_{2D}}=0.039$ is obtained. Using

$$E_B=\frac{13.6\mu}{\epsilon^2} \tag{3}$$

for the exciton binding energy, the binding energy $X_{2D}=3.4$ meV is obtained. The extrapolated transition energy of X_{2D} from Fig. 3 is 1.5140 eV. Adding to this the exciton binding energy of 3.4 meV gives a band gap of 1.5174 eV. This is 2.1 meV smaller than the band gap of GaAs 1.5195 eV. This reduction in band gap is attributed to many-body interactions. The effect of many-body interactions has been calculated by Jogai[5] for GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ multiple quantum wells. The calculation was extended to include surface states and was applied to the GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructure being investigated. An electron carrier concentration of 1.16×10^{12} cm^{-2} was calculated, which is in good agreement with the measured value of 1.07×10^{12} cm^{-2}. An upper limit of 5 meV was calculated for the band-gap renormalization. This is also consistent with the value (2.1 meV) determined from the zero-field transition energy and the measured diamagnetic shift. In Fig. 2 the increased linewidths of the X_{2D}-related transitions are observed. This would be expected as explained in Sec. I.

In conclusion, we have shown the presence of two-dimensional excitons in modulation-doped heterostructures in which the electron is associated with the 2DEG. The excitons are formed in a region of the structure where the binding energy is reduced by screening effects, and where band-gap renormalization occurs due to many-body interactions.

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