Electric-field-induced ionization of negatively charged excitons in quantum wells

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(Received 17 October 1996)

We study optical spectra of remotely doped quantum wells in which the electric field and electron density can be varied independently. We demonstrate that the second electron binding energy of the negatively charged exciton (X^-) is dramatically reduced by a relatively small electric field applied normal to the quantum well. [S0163-1829(97)52004-2]

The band-edge region of the optical spectra of semiconductors is dominated by resonances due to excitons; the bound states of the electron-hole attraction. In bulk semiconductors these excitons are ionized by a small applied electric field.[1] The ratio of the exciton binding energy and diameter gives a classical estimate for the ionization field of about 2.5 kV/cm for GaAs. In contrast, the confining potential barriers of a quantum well (QW) heterostructure prevent the dissociation of the electron and hole under an electric field applied normal to the layers, allowing the exciton to survive fields far in excess of the bulk ionization value. The polarization of the electron and hole wave functions toward opposite faces of the QW causes a strong redshift of the exciton transition energy, accompanied by some, but not a total, reduction in the oscillator strength and exciton binding energy.[2,3] This phenomenon, known as the quantum confined Stark effect, has attracted a great deal of research interest, because of its possible utilization in electro-optic devices.

We report here the effect of an electric field upon the negatively charged exciton X^-, which is the bound state consisting of two electrons and a hole. X^- is observed in the optical spectra of QW's containing a few 10^{10} cm^{-2} excess electrons, where it produces an optical transition ($X^- \rightleftharpoons e^- + \text{photon}$) whose energy lies below that of the neutral exciton (X) by an amount roughly equal to the binding energy of the second (excess) electron (E_{2b}). Although E_{2b} is too small for X^- to be resolved in bulk semiconductors, its value is greatly enhanced in QW's by the confinement of the electron and hole wave functions, allowing X^- to be observed in a range of QW structures.[4–8] The positively charged exciton X^+, consisting of two holes and one electron, is also stable and has been reported in the optical spectra of QW's containing excess holes due to remote doping with acceptors.[9] Indeed X^+ is even observed in undoped GaAs/Al$_x$Ga$_{1-x}$As QW's due to the unintentional incorporation of p-type impurities in the barrier layers during growth.[10]

Several of the X^- studies have been performed on remotely doped QW's where the excess electron density can be continuously varied using a metal Schottky gate contact on the sample surface. When a gate bias is applied so as to deplete the QW of nearly all charge, its optical spectra are dominated by transitions due to neutral excitons. As the excess electron density in the QW is increased, the transition strength of X weakens sharply in both excitation and emission spectra, while X^- strengthens correspondingly, due to the increasing area of the QW covered by the excess electrons.[5] At higher electron densities, the X line is completely quenched from the spectra, while X^- shifts to lower energy due to both the exchange-correlation potential of the electron-electron interaction and the electric field caused by the charge in the QW. Excitation spectra show X^- evolving smoothly into the Fermi edge transition seen for dense electron gases.[5]

In this work we study excitonic transitions in a remotely doped QW structure, which has both front and back gate contacts on either side of the QW. This allows us to vary the electric field across the QW, in addition to its excess electron density. We find that X^- is much more sensitive to applied electric fields than X. Essentially this derives from the additional repulsion of the two electrons in X^-. At zero electric field, this repulsion is countered by the attraction of the electrons to the hole, producing a relatively small net binding. However, when an electric field is applied normal to the QW, the electron and hole wave functions are polarized in opposite directions, thereby weakening slightly their attraction, but reducing sharply the net binding of X^-. The experimental data are compared to a Monte Carlo calculation of the exciton energies.

The sample studied here was a remotely doped 300 Å GaAs/Al$_{0.33}$Ga$_{0.67}$As QW grown by molecular-beam epitaxy on a (100) oriented GaAs substrate. The layer structure consisted of 1 μm GaAs, 1 μm Al$_{0.33}$Ga$_{0.67}$As, 0.5 μm GaAs(25 Å)/Al$_{0.33}$Ga$_{0.67}$As(25 Å) superlattice, 300 Å GaAs QW, 600 Å undoped Al$_{0.33}$Ga$_{0.67}$As spacer, 2000 Å Al$_{0.33}$Ga$_{0.67}$As Si doped (10^{17} cm^{-3}), and 170 Å GaAs cap. It was processed into mesas, with several Au$_x$Ge$_{1-x}$Ni Ohmic contacts to the QW layer. A semitransparent NiCr Schottky barrier was evaporated on the top surface to act as the front gate, while another contact was made to the back of the substrate to act as the back gate. Both the front and back gates were biased with respect to the Ohmic contacts, in order to vary the electron density and electric field across the QW.

Photoluminescence (PL) spectra were recorded with the device maintained at a temperature of 2 K, as a function of

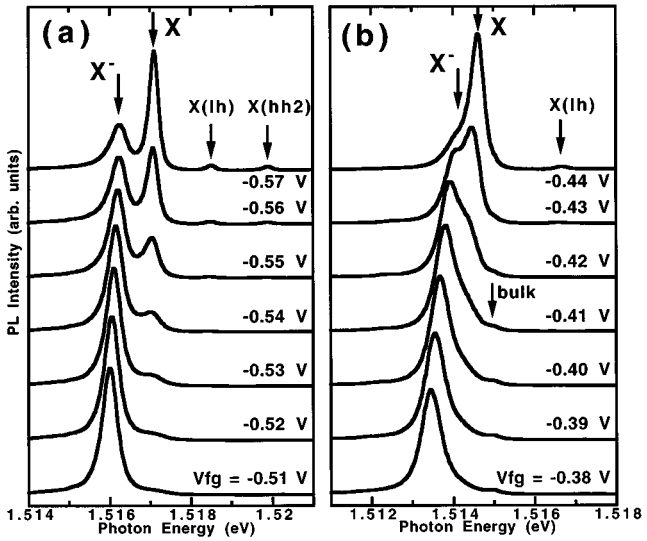

FIG. 1. PL spectra recorded on a remotely doped 300 Å GaAs QW for different front gate biases and fixed back gate biases of (a) 0.0 V and (b) −1.0 V. The sample temperature was 2 K.

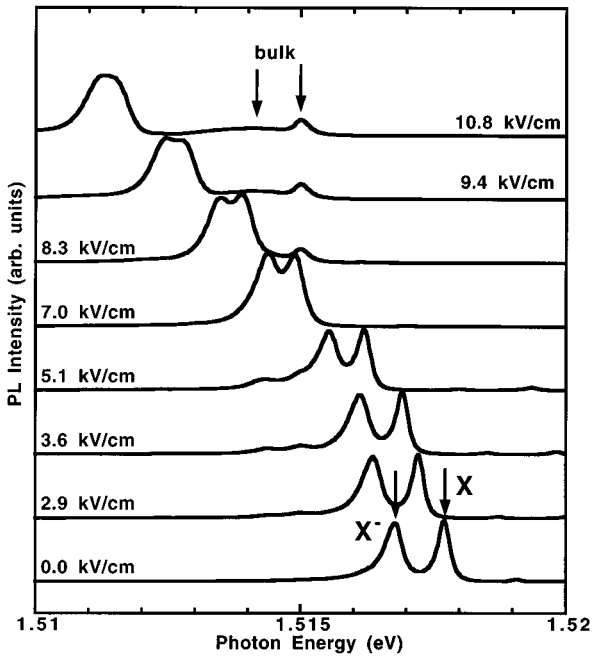

FIG. 2. PL spectra recorded on a remotely doped 300 Å GaAs QW for different back gate biases. The front gate bias has been set for each spectrum, so that the X and X^- peaks have roughly equal intensity. The electric fields indicated for each spectrum are deduced from the Stark shift of the X line.

both front and back gate biases. Figure 1(a) plots PL spectra recorded with different front gate biases (V_{fg}), for a fixed back gate bias (V_{bg}) of 0.0 V. These spectra are almost identical to those we have measured previously[5] on similar structures without a back gate. The doublet is due to the recombination of X and X^-, the latter according to $X^- \rightarrow e^- +$photon. The observed splitting of ~0.87 meV is close to the expected E_{2b} of X^- in a 300 Å GaAs QW.[5] At the most negative V_{fg} in Fig. 1(a), where the excess electron density in the QW is minimal, the PL is dominated by the higher energy component of the doublet due to X. Notice that as V_{fg} is increased, the peak due to X weakens, while that due to X^- strengthens, due to the enhancement of the population of X^- over X as the excess electron density in the QW increases. At higher electron densities than those shown in Fig. 1(a), the peak due to X^- broadens and shifts to lower energy, thereby forming the broad PL band which is the signature of a dense electron gas.[5]

Figure 1(b) again plots PL spectra taken for different V_{fg}, but this time for a fixed V_{bg} of −1.0 V. The electric field created by the back gate voltage shifts the band-edge PL to lower energy, due to the quantum confined Stark effect. Notice that, as in Fig. 1(a), the PL spectra again display a doublet, but now the splitting of the lines is significantly reduced to ~0.54 meV. The assignment of the two strong PL lines to X and X^- is again consistent with their dependence on the excess electron density. At the lowest electron densities, the higher energy peak due to X dominates. Adding excess electrons weakens X, with a corresponding strengthening of X^-. The front gate voltage where the PL intensity transfers from X to X^- is less negative in Fig. 1(b) than 1(a), because the applied negative back gate voltage partially depletes the electron density in the QW.

Figure 2 plots PL spectra recorded for different back gate biases. For each spectrum, the front gate bias has been fixed so that the X and X^- PL peaks have almost equal intensity. Both the X and X^- lines shift to lower energy with increasingly negative back gate bias. The redshift of the X line is due to the quantum confined Stark effect caused by the electric-field-induced polarization of the electron and hole envelope functions to opposite faces of the quantum well. By comparing the observed redshift to the calculated (see later) variation of the X energy with field we are able to determine an average electric field across the well at each bias. Regarding the electric field across the QW as uniform, and thereby ignoring the band bending caused by the excess electron charge, is a reasonable approximation at the very dilute electron densities studied here. The electric fields so deduced are consistent with the reduction in the electron density caused by the same back gate bias for a fixed $V_{fg}=0.0$ V.

Of particular interest here is that the X^- peak shows a smaller redshift than X with negative back gate bias, so that their splitting decreases. The splitting of the X and X^- peaks is essentially equal to the binding energy of the second electron in X^-, defined as $E_{2b}=(E_X+E_{e^-})-E_{X^-}$, where E_{X^-}, E_X, and E_{e^-} are the energies of an isolated X^-, X, and e^-, respectively. Hence the decreasing separation of X and X^- indicates that E_{2b} is sharply reduced by an applied electric field. Figure 3 plots the splitting, determined from a best fit to the spectra, against the applied electric field, deduced from the Stark shift of the X line. It can be seen that an electric field of around 10 kV/cm is sufficient to reduce E_{2b} to a value close to the linewidth, at which point the spectral splitting becomes difficult to resolve.

The X peak has maximum photon energy under positive back gate voltage. The measured Stark shift suggests that there is a small electric field of ~3 kV/cm across the QW when the back gate is a left open circuit. This residual field causes an appreciable reduction in the measured splitting. The results presented here demonstrate that any experimental

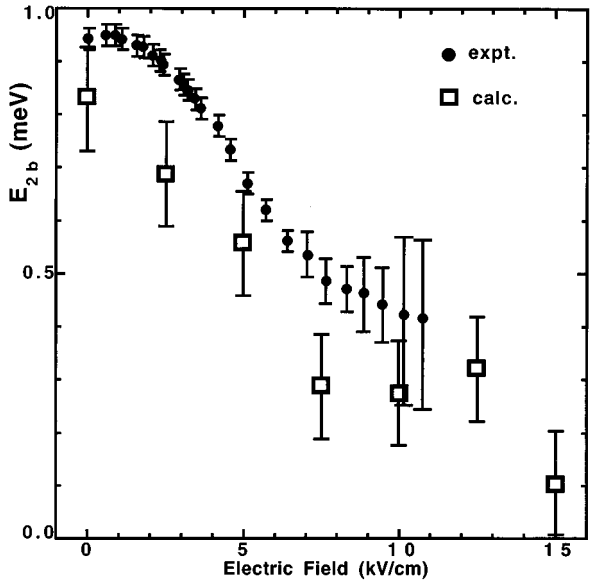

FIG. 3. Electric field dependence of the second electron binding energy, as determined from the splitting of the X and X^- peaks (closed circles) and a Monte Carlo calculation (open squares).

study of X^-, even in structures without a back gate, will be sensitive to extrinsic electric fields across the QW.

The sharp reduction in E_{2b} with applied electric field can be explained by the polarization of the electron and hole wave functions along the direction normal to the plane of the QW. Since the hole is polarized to the opposite face of the QW to the two electrons, the electric field increases the average electron-hole separation, while having less effect upon the interelectron distance. Hence the polarization of the wave functions weakens the attractive forces in X^- relative to the repulsive ones, thereby reducing the net binding energy.

Although the data in Fig. 3 suggest that E_{2b} decreases less sharply at the highest electric fields, it should be remembered that the two peaks are difficult to resolve spectrally at these fields and the determined splitting has thus a large associated error. At these fields the splitting may also be approaching the homogeneous linewidth, which has been measured to be a few tenths of an meV in a GaAs QW similar to ours.[11] When E_{2b} is comparable to the homogeneous linewidth, the lifetime is too short to make a meaningful distinction between X^- and X plus a free electron. The excess electron can then be regarded as ionized.

In contrast to the behavior for X^-, the absence of repulsive forces in the neutral exciton results in the binding of the first electron persisting to much higher electric fields. The Monte Carlo calculation, discussed below, yields a reduction in the X binding energy of 33% at 10 kV/cm for a 300 Å GaAs QW. The PL spectra show a sharp X line to remain beyond the electric fields where E_{2b} is greatly reduced.

Also plotted in Fig. 3 are the results of an effective mass Monte Carlo calculation of E_{2b} for a 300 Å GaAs QW with finite potential barriers. The statistical noise associated with the calculation is indicated by the vertical error bars in Fig. 3. The conduction and valence bands are assumed parabolic and isotropic with effective masses of 0.067 and 0.335, respectively, while the band offsets are taken as 0.247 and 0.144 eV, respectively. Further details of the calculation will be presented elsewhere. Notice that the calculation reproduces the trend of the experimental data and accurately predicts the electric field where E_{2b} is sharply reduced. In general, the calculated E_{2b} are slightly lower than the measured ones. The discrepancy may be resolved by considering a more realistic valance band dispersion or by taking different effective masses in the well and barriers.

In conclusion, a modest electric field applied normal to a QW causes a sharp reduction in the second electron binding energy of X^-. The electric field polarizes the hole to the opposite face of the QW from the two electrons, thereby reducing the electron-hole attraction, while having less effect upon the electron-electron repulsion, causing a reduction in the net binding energy. Under a modest applied field the excess electron loses nearly all binding energy to the exciton and a distinct peak due to X^- is no longer resolvable.

We thank J.L. Osborne for processing the samples. Part of this research at Cavendish Laboratory was funded by ESPRC, UK.

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