Increased screening of the hydrogenic donor due to modulation doping in quantum wells

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Screening of the hydrogenic donor at the center of the well in *p*-type modulation-doped $Al_xGa_{1-x}As$-GaAs quantum wells was measured by monitoring the free to bound transition, free hole to donor. Undoped, center of the well doped, and center of the barrier doped samples were investigated. The screening increased, as measured by the reduction in the binding energy of the donor, in the sequence undoped, center of the well doped, and center of the barrier doped samples. The screening efficiency increases as the donor ion is moved farther away from the center of the well. The reduction in the donor binding energy, due to screening from carriers introduced by center of the barrier doping, agrees reasonably well with the calculated value for modulation-doped quantum wells of the same carrier density.

INTRODUCTION

The screening of the hydrogenic donor at the center and edge of the well in modulation-doped quantum wells (QW's) was investigated by Guillemot.[1] The quantum well is a convenient vehicle for studying screening of donors since the donor binding energy as a function of well size has been well established.[2] Also, the doping impurities can be placed either in the well or in the barrier in a controlled manner. In the current experiment the transition that has been used to study the effect of screening on the donor binding energy is the free to bound transition, free hole to donor at the center of the well. This transition is identified by the fact that it has a larger diamagnetic shift than either the free exciton or the bound exciton transitions. The free to bound transition has two contributions to the diamagnetic shift, one being the diamagnetic shift of the donor, the other is the Landau energy of the hole.[3] The free carriers contributing to screening in the present experiment are holes. Acceptor doping is used because it results in a fairly dominant free to bound transition, free hole to donor. In the case of donor doping the dominant transition is the donor bound exciton with the free to bound transition not being seen at all in many donor-doped samples. The donor binding energy can be determined directly from the free to bound transition. The donor binding energy is the difference between the subband energy and the free to bound transition energy. The subband energy is obtained from the heavy-hole free-exciton (HHFE) energy by adding to the HHFE energy the binding energy of the exciton. The exciton binding energy for these quantum wells is well established.[4]

In the current experiment three samples were investigated. The samples consisted of nominally 300-Å $Al_{0.3}Ga_{0.7}$ As/GaAs QW's with 30 repeats in each structure. Sample 1 was undoped, the other two samples were Be doped with the doping position for sample 2 at the center of the well (CW) and the doping position for sample 3 at the center of the barrier (CB). The donor binding energy decreases as the doping position is moved from the CW to the CB reflecting increased screening as the doping ion is moved farther away from the CW. The negative-doping ion tends to neutralize the screening effect of the positive carrier. For each doping position and doping concentration the number of free carriers at the center of the well was calculated. The free carriers, not neutralized by the presence of negative ions, contribute to the screening of the hydrogenic donor. The donor binding energy was measured to be 9.9 meV in the undoped sample, 7.9 meV in the sample doped at the CW, and 6.3 meV in the sample doped at the CB. This reflects the increased screening due to modulation doping where the doping ion resides outside the well.

It was noted that the intensity of the free to bound transition increases as the screening increases. As the screening increases the donor binding energy is reduced resulting in a larger electron orbit for the donor. The larger orbit increases the overlap with the free holes, resulting in increased intensity of the free to bound transition.

EXPERIMENTAL ARRANGEMENT

The samples used in this experiment were all nominally 300-Å $Al_{0.3}Ga_{0.7}As$/GaAs QW's with 30 repeats in each structure. Sample 1 was undoped. Sample 2 was delta doped with Be acceptors at the CW with a nominal sheet acceptor concentration of 3×10^{11} cm^{-2}. Sample 3 was doped at a concentration of $\sim10^{17}$/cm^3 over the central 20 Å of the barrier. The CW-doped sample had 100-Å $Al_{0.3}Ga_{0.7}As$ barriers. The CB-doped sample had 60-Å barriers with Be doping over the central 20 Å of each barrier. The structures were grown in a Varian Gen II solid source molecular-beam-epitaxy (MBE) growth apparatus on GaAs substrates. The substrates were

misoriented 6° from (001) towards (111)A which allowed the production of very-high-quality interfaces at the growth temperature of 560 °C. The growth rates were 0.7 and 1.0 monolayer per second for GaAs and $Al_{0.3}Ga_{0.7}As$, respectively.

The optical transitions from the samples were studied in photoluminescence (PL) which was excited with an Ar^+ ion laser pumped tunable dye laser using Styryl 9 dye. The pump power density was approximately 500 mW cm^{-2}. The measurements were made at 2 K with the sample immersed in liquid He. A magnetic field oriented perpendicular to the growth direction of the sample was used to study the diamagnetic shifts of the optical transitions. The spectra were analyzed with a high-resolution 4-m spectrometer equipped with an RCAC31034A photomultiplier tube for detection.

RESULTS AND DISCUSSION

The PL spectra for sample 1 (undoped) are shown in Fig. 1. The solid curve shows the transitions in zero magnetic field while the dashed curve is for an applied field of 36 kG. It is seen that the free to bound transition has an appreciably larger diamagnetic shift than the HHFE transition. The identification of the free to bound transition has been reported previously.[3] The calculated binding energy of the HHFE in a 300-Å well is 5.7 meV.[4] Adding this energy to the HHFE transition energy gives a heavy-hole subband energy of 1.5257 eV. Subtracting from this the free to bound transition energy, a donor binding energy of 9.9 meV is obtained. The calculated donor binding energy for a 300-Å well is ~9.0 meV.[2]

The PL spectra for sample 2 (doped CW) are shown in Fig. 2. Again the solid curve shows the transitions in zero field while the dashed curve is for an applied field of 36 kG. Three transitions are observed, the HHFE, the free to bound transition, and the neutral-acceptor bound exciton transition (A^0,X). The free to bound transition is identified by its larger diamagnetic shift. The HHFE and A^0,X transitions have nearly the same diamagnetic shift as would be expected since the exciton is loosely bound to the acceptor. As in the undoped sample the heavy-hole subband energy is obtained by adding the exciton binding energy to the energy of the HHFE transition giving an energy of 1.5253 eV. When the energy of the free to bound transition is subtracted from this energy a donor binding energy of 7.9 meV is obtained. This sample was doped with Be at the center of the well with a nominal sheet concentration of 3×10^{11} cm^{-2} per well. In this case the negative ions are located in the well which will have a neutralizing effect on the ability of the holes to screen the hydrogenic donor at the center of the well. However, the measured donor binding energy is reduced by 2 meV from that measured for the undoped sample suggesting that screening of the donor is occurring.

The PL spectra for sample 3 (doped CB) are shown in Fig. 3. As before the solid curve is in zero field while the dashed curve is for a magnetic field of 36 kG. The HHFE and free to bound transitions are observed, the free to bound transition having the larger diamagnetic shift. As before the heavy-hole subband energy is obtained by adding the exciton binding energy to the HHFE transition energy giving an energy of 1.5247 eV. Subtracting from this the energy of the free to bound transition, one obtains a donor binding energy of 6.3 meV. This sample was doped CB with Be at a concentration of ~10^{17} cm^3 over the central 20 Å of the barrier. The barrier width for this sample was 60 Å. While the hole concentration for this sample was less than that for sample 2 the screening is increased. The increased screening is explained by the fact that the negative ions in this sample are located at the center of the barrier while

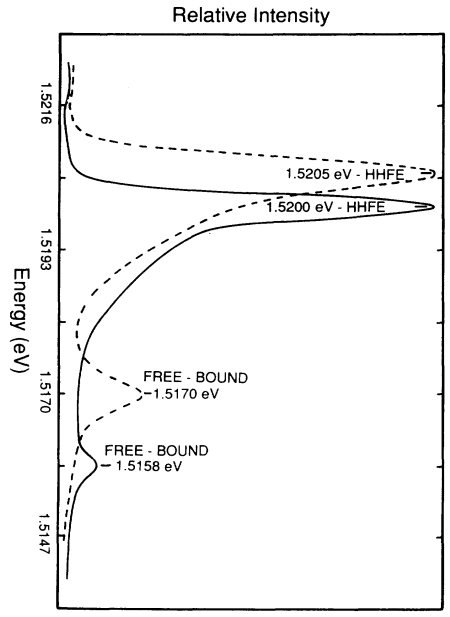

FIG. 1. PL spectra for sample 1 (undoped); solid curve is for $H=0$, dashed curve is for $H=36$ kG.

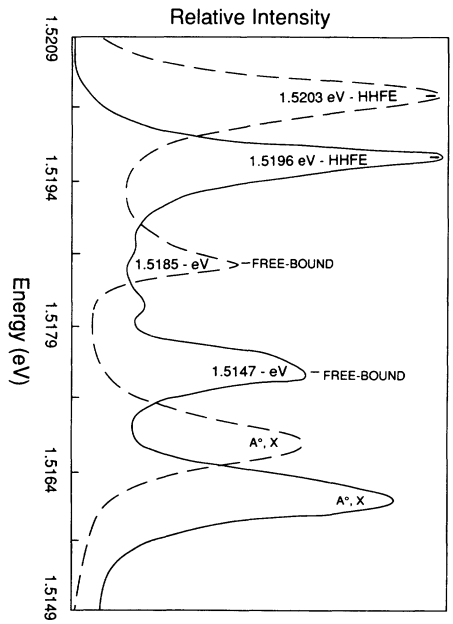

FIG. 2. PL spectra for sample 2 (doped CW); solid curve is for $H=0$, dashed curve is for $H=36$ kG.

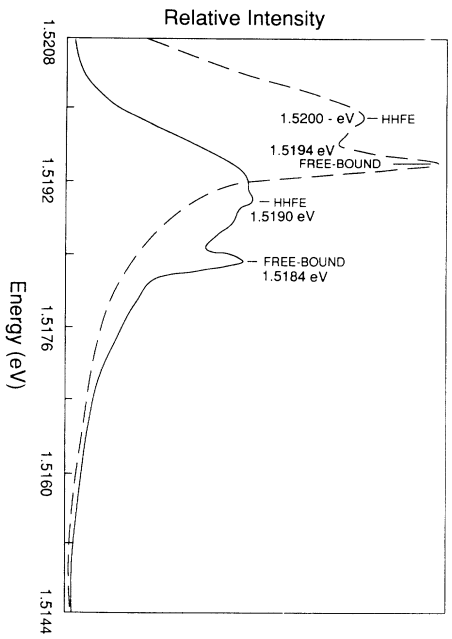

FIG. 3. PL spectra for sample 3 (doped CB); solid curve is for $H=0$, dashed curve is for $H=36$ kG.

the holes are positioned in the well. The negative ions are less effective in neutralizing the screening effect of the holes on the hydrogenic donor in this configuration. In going from Fig. 1 to Fig. 2 to Fig. 3 one observes that the free to bound transition is moving towards the HHFE transition in energy. This reflects the decrease in the donor binding energy due to increased screening. One also observes an increase in the free to bound transition intensity. This is explained by the increased orbital extent of the electron on the donor with decreased donor binding energy. The increased orbital extent gives greater overlap of the donor with the free hole resulting in increased intensity.

The carrier density at the center of the well was calculated for both the center of the well and the center of the barrier doping. The hole density was calculated self-consistently with many-body effects included. The eigenstates were calculated from a four-band $\mathbf{k}\cdot\mathbf{p}$ model that uses a basis consisting of electron, light-hole, heavy-hole, and split-off states. The Hartree part of the Coulomb interaction was computed from the Poisson equation and the exchange correlation part from density-functional theory within the local-density approximation. Following the eigenstate calculation, the hole density was calculated from Fermi-Dirac statistics. The process was repeated until it converged.[5]

The calculated density of holes at the center of the well resulting from CB doping in sample 3 was $\sim 10^{16}$ cm^{-3}. The screening of the hydrogenic donor by the carriers reduced the binding energy by 2.7 meV from the calculated value. The calculated reduction in binding energy due to screening by this carrier concentration taken from Fig. 2 in Ref. 1 is ~ 2.3 meV. This value is for a 200-Å quantum well. The quantum well investigated in this study is 300 Å; however, the qualitative agreement with theory is quite reasonable. The calculated density of holes at the center of the well resulting from CW doping was $\sim 2\times 10^{17}$ cm^{-3}. While the hole density at the CW in sample 2 was an order of magnitude greater than in sample 3, the screening was less. The donor binding energy in sample 2 was 7.9 meV and in sample 3 it was 6.3 meV. The decreased screening in sample 2 is due to the neutralizing effect that the doping ions have on the screening efficiency of the positive carriers.

In conclusion, we have shown that the screening efficiency increases as the dopant ion is moved farther away from the center of the well. This was determined from the decrease in the binding energy of the hydrogenic donor at the center of the well as the position of the doping ions was moved from the center of the well to the center of the barrier.

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