Effect of the electron Coulomb potential on hole confinement in II-VI quantum wells

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We report a pronounced effect of an additional hole confinement in the electron Coulomb potential on giant splitting and oscillator strength of the exciton Zeeman patterns in $CdTe/Cd_{0.75}Mn_{0.25}Te$ quantum-well structures. Measuring oscillator strength and Zeeman splitting as a function of the quantum-well width and/or an external magnetic field by resonance reflection spectroscopy we demonstrate the transition from a hole subject to a net potential well to that confined to the electron Coulomb potential occurring in quantum wells thicker than 30 Å. This transition is also found in superlattices where the electron wave function changes its character from three to two dimensional with an increase of the superlattice period. Analyzing the magneto-optical data taken above and below the transition, we conclude that an additional hole confinement reduces a hole wave-function penetration into semimagnetic barriers and decreases the strength of the exchange interaction of holes with magnetic ions.

Recently there have been a number of experimental studies on the optical properties of wide gap II-VI compound semiconductor quantum wells (QW) where strong exciton effects and rather small valence-band offsets have been demonstrated.[1-4] In these heterostructures the electron is tightly confined in QW's and the Coulomb potential acting on the hole significantly modifies its effective confinement potential in the direction normal to the QW plane. The combined effective confinement for holes arises from the net quantum well and the Coulomb interaction averaged over a quasi-two-dimensional electron distribution.[5-7] Noteworthy is that it is not critical to include an additional hole confinement to bring theory and experiment into agreement in III-V QW's where the valence-band offsets are much larger than the electron Coulomb potential strength.[8] While an additional confinement potential for holes has been taken into account in order to extract band offsets in II-VI QW's,[1-3] direct experimental evidence for its existence has not yet been demonstrated. There is considerable interest in studying exciton effects in the QW model system CdTe/(Cd,Mn)Te where the transition from holes which are subject to the combined effective potential to those confined to the bare QW potential can be realized (i) in thin QW's where the hole confinement energy exceeds the depth of the electron Coulomb potential well and (ii) in short-period superlattices (SL) where the electron Coulomb potential well vanishes due to the three-dimensional (3D) character of the electron wave function. The barrier material in these structures is the diluted magnetic semiconductor (Cd,Mn)Te which has a giant g factor at low lattice temperatures. This gives the opportunity to alter the barrier heights substantially by external magnetic fields and to investigate the effect of the Coulomb potential on the penetration of the hole wave function into the Mn-rich barriers. This effect is of key importance for the problem of 2D magnetic polaron formation in quantum wells with semimagnetic barriers.[9]

In this paper we report experimental evidence of the existence of a Coulomb potential well for heavy holes which is induced by strongly confined electrons in $CdTe/Cd_{1-x}Mn_xTe$ quantum-well structures. To elucidate the electron Coulomb potential effects we have measured the exciton oscillator strength as a function of the QW width L_z using the resonance exciton reflectivity line-shape analysis.[10,11] We find that for QW's thinner than 30 Å this dependence can be described by quasi-2D excitons formed by electrons and holes confined to the net potential wells, whereas for thicker QW's it is governed by the hole confinement to the effective well with a large Coulomb contribution. Further, analyzing Zeeman splittings of the exciton resonances we conclude that a substantial asymmetry of the splitting observed in the former case can be attributed to hole confinement in the net potential well. In the latter case, the asymmetry appears to be suppressed since the holes are confined to a large extent by the electron Coulomb potential well and are only weakly sensitive to the change of the (Cd,Mn)Te barrier height. A clear support of this assumption comes from a comparison of the experimental and calculated Zeeman splittings in SL's with 3D or 2D character of the electron wave function. A strong indication of an additional hole confinement is also found in the oscillator strength behavior of the exciton Zeeman patterns in the multiple QW's where the magnetic-field effect on the oscillator strength appears to be suppressed.

$CdTe/Cd_{0.75}Mn_{0.25}Te$ QW structures and superlattices were prepared by molecular-beam epitaxy on (100)-oriented CdTe substrates.[12] The structures were grown on a 0.6-μm-thick buffer layer of $Cd_{0.75}Mn_{0.25}Te$ and contain either a set of single QW's separated by 1000-Å-thick $Cd_{0.75}Mn_{0.25}Te$ barrier layers, or a 50-period superlattice with equal thickness of the well and barrier layers,

$l_z/l_b = 12$ Å/12 Å, 30 Å/30 Å and 60 Å/60 Å. The QW widths ranged from 15 to 120 Å. Reflection spectra were taken at the Brewster angle geometry with light polarized in the incidence plane. Circularly polarized reflectivity at normal incidence geometry was measured at magnetic fields up to 7.5 T applied perpendicular to the QW layers.

Circles in Fig. 1 show the heavy-hole exciton oscillator strength (or longitudinal-transverse splitting) in $CdTe/Cd_{0.75}Mn_{0.25}Te$ single quantum wells normalized to that of bulk CdTe as a function of the QW width. The exciton parameters were deduced from the resonance reflectivity line-shape analysis.[10,13] The oscillator strength shows a monotonic increase in the range of QW width down to 30 Å and then a dramatic enhancement for thinner QW's. This behavior signals a possible changing of the confinement potential for holes which are weakly confined particles with decreasing QW width. The specific form of the confining potential is expected to result in different confinement conditions for holes in thin and thick QW's as depicted in the insets of Fig. 1. The figure also includes results of our calculations of the oscillator strength: (i) in the net potential-well model with the in-plane electron-hole Coulomb potential determined by $e^2(\rho\varepsilon_b)$, as shown by the solid line, where ε_b is the background dielectric constant and ρ the relative electron and hole coordinates in the QW plane; (ii) taking into account an additional heavy-hole confinement perpendicular to the QW plane due to the adiabatic Coulomb potential created by the electron in the exciton (dashed line). The hole confinement potential is approximated by parabola. This approximation is valid for thick QW's where the adiabatic Coulomb confinement dominates. In the calculations, details of which will be published,[13] we assume $\Delta E_v \simeq 0.12\Delta E_g$ and take into account the strain-induced band offset $E_{hh} = 11$ meV for heavy holes.[15] For QW's thicker than 32 Å the data appear to be in excellent agreement with the predictions of the latter model and to indicate that the hole is subject to the combined effective potential with a dominant contribution from the adiabatic Coulomb potential. The dramatic enhancement of the oscillator strength by more than a factor of 30 observed in the thinner wells seems to be in line with the predictions of the former model. It should be noted that a discrepancy between the experimental and theoretical data found in thick QW's for the former model could not be improved even using the quasi-2D instead of the 2D Coulomb potential with a set of reasonable parameters.[13]

To elucidate further the electron Coulomb potential effect on the hole confinement we present the results of an investigation of the exciton Zeeman splittings in two QW's with L_z less and greater than 30 Å. The hole contribution dominates the exciton Zeeman splitting due to a smaller value of the electron exchange constant in comparison to that of the holes.[16] We use this fact for the evaluation of the penetration of the hole wave function into the semimagnetic barriers.

The Zeeman splittings of the heavy-hole excitons in magnetic fields parallel to the growth axis are shown in Fig. 2 for two QW's of widths 23 and 60 Å. The larger splitting observed in the thinner QW is connected with the greater penetration of the hole wave function into the (Cd,Mn)Te barriers. Moreover, one can see a substantial asymmetry of this splitting in contrast to the symmetric behavior of Zeeman patterns in the thicker QW. The asymmetry shows that the hole wave-function penetration into the barriers depends on an external magnetic field[1,3] and indicates the hole confinement to the net po-

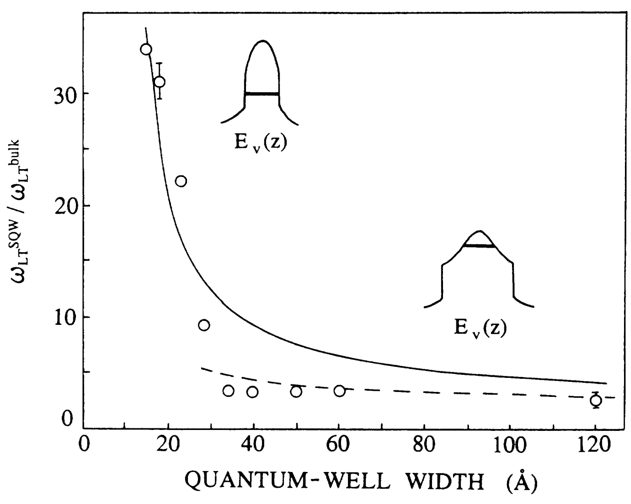

FIG. 1. The exciton longitudinal-transverse splitting (oscillator strength) normalized to $\hbar\omega_{LT}^{bulk} = 0.67$ meV of bulk CdTe (Ref. 14) as a function of the quantum-well width in $CdTe/Cd_{0.75}Mn_{0.25}Te$ single-QW structures: experiment—circles; calculations for hole confinement in the net potential well—solid line; in the combined effective potential—dashed line; with effective masses of $m_e = 0.09$, $0.15m_0$ and $m_{hh} = 0.5$, $0.75m_0$ in the well and barrier layers, respectively. Insets illustrate schematically the hole confinement in thin and thick QW's.

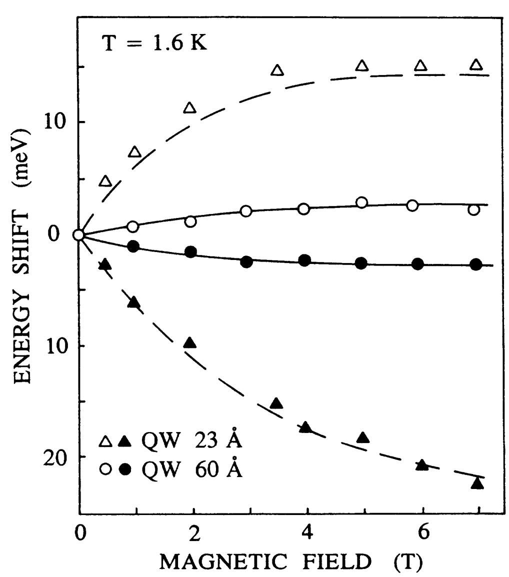

FIG. 2. Zeeman splitting of heavy-hole excitons in 23- and 60-Å-thick single QW's. Open signs σ^- and closed signs σ^+ circular polarizations. Dashed lines are computed in the net potential-well model, solid line takes into account the hole confinement to the combined effective potential.

tential well. It is connected with different potential barriers for the particular hole spin components resulting from the giant spin splitting of the valence-band states in the (Cd,Mn)Te barrier layers. Results of our calculation with the net potential wells shown by dashed lines in Fig. 2 are in good agreement with the experimental data. The absence of the asymmetry in the 60-Å-thick QW can be explained by a weak sensitivity of the hole wave function on the net potential strength when the hole is confined to the electron Coulomb potential well. Indeed, the observed behavior is well described, taking into account an additional hole confinement,[13] as shown by the solid lines in Fig. 2.

To support this hypothesis we present the exciton Zeeman splittings in SL's with the 3D and 2D character of the electron wave function. A 12 Å/12 Å SL reveals a large and symmetric splitting, shown in Fig. 3(a), both signaling an existence of wide electron and hole minibands in agreement with the oscillator strength measurements.[11] This behavior is excellently described by the magnetic-field-induced changing of the Kronig-Penney potentials, as the solid curve shows in Fig. 3(a). To take into account the tuning of the SL potential for electrons and holes in the presence of external magnetic fields, we use a well-established formulation of the hh-valence- and conduction-band splittings in semimagnetic barriers, which can be written as

$$\Delta V_{\pm}^{hh} = \pm \tfrac{1}{3}\beta N_0 \bar{x} J \langle S_z \rangle \ , \qquad \Delta V_{\pm}^{e} = \pm \alpha N_0 \bar{x} I \langle S_z \rangle \ , \tag{1}$$

for hole (electron) spin $\pm J(I)$ antiparallel and parallel to the magnetic field, respectively. Here $N_0\bar{x}$ is the effective concentration of the Mn ions in the paramagnetic phase, β and α are the hole and electron exchange coefficients, and $\langle S_z \rangle$ is the thermodynamical average of the ion spin in the direction of the applied field which is described by the Brillouin function $B_{5/2}$. To reflect changes in the paramagnetic behavior due to the antiferromagnetic Mn-Mn spin coupling, the Brillouin function is modified by including a correction factor T_{AF}. Using the conduction- and valence-band exchange coefficients evaluated for bulk (Cd,Mn)Te, $\alpha N_0 = 220$ and $\beta N_0 = 880$ meV,[16] we have obtained good agreement with the experimental data for $\bar{x} = 0.05$ $T_{AF} = 2.4$ K, and the total valence-band offset of 59 meV [see Fig. 3(a)].

Being a set of isolated QW's the 60 Å/60 Å SL shows the weak and symmetrical exciton Zeeman splitting displayed by circles in Fig. 3(b). Calculation in the model of the net SL potentials with the above parameters $\bar{x}$, T_{AF}, and ΔE_v predicts larger splitting and substantial asymmetry (dashed line). To obtain an adequate description of the experimental splitting in SL's with 2D character of the electron wave functions, we take into account the effect of the electron Coulomb potential on the hole confinement. For a quantitative evaluation of this effect, it is convenient to describe the Zeeman splittings in the framework of penetrating wave functions:

$$E_{\pm} = \pm N_0 \bar{x} \langle S_z \rangle (\tfrac{1}{3}\beta J \gamma_h + \alpha I \gamma_e) \ , \tag{2}$$

where γ_h (or γ_e) is the probability of finding a hole (or an electron) in the semimagnetic barriers. The absence of

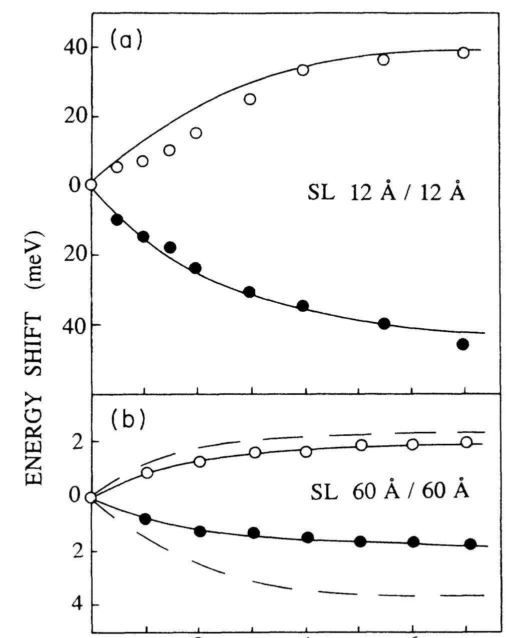

FIG. 3. Zeeman splitting of heavy-hole excitons in $CdTe/Cd_{0.75}Mn_{0.25}Te$ superlattices. Open signs σ^- and closed signs σ^+ circular polarizations. Solid lines in (a) and dashed lines in (b)—calculations with the net SL potential; solid lines in (b)—calculations with the combined effective potential for holes. $T = 1.6$ K.

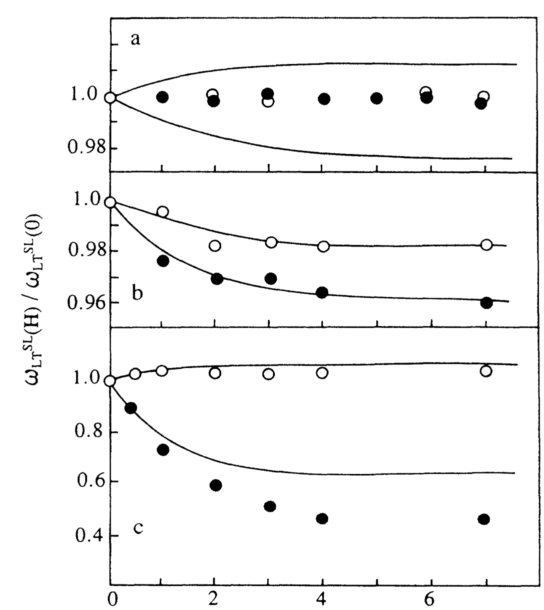

FIG. 4. Normalized oscillator strengths of the exciton Zeeman components taken in σ^+ (full signs) and σ^- (open signs) circular polarizations from $CdTe/Cd_{0.75}Mn_{0.25}Te$ superlattices with periods of 120 Å, (b) 60 Å, and (c) 24 Å versus an external magnetic field. Solid lines are calculated in the Kronig-Penney model with net SL potentials.

the asymmetry in the Zeeman splitting allows us to suggest that γ_h is independent of the magnetic field. γ_e is calculated in the Kronig-Penney model with the net SL potential. The best fit to the experimental data is obtained with $\gamma_h = 0.056$, as shown by the solid curve in Fig. 3(b). However, the Kronig-Penney model calculation with net SL potentials gives $\gamma_h = 0.069$. Thus, the additional confinement of holes caused by the electron-hole Coulomb interaction decreases the penetration of hole wave function into barriers by about 20%. It also leads to a reduced asymmetry and value of the Zeeman splitting observed in the 60 Å/60 Å SL as compared to those obtained in the net SL potential model.

The next manifestation of the Coulomb potential well we have found by studying the exciton oscillator strength behavior of Zeeman patterns. The oscillator strength appears to be independent of magnetic fields in a 60 Å/60 Å SL, to decrease weakly in a 30 Å/30 Å SL and is strongly influenced by fields in 12 Å/12 Å SL's, as shown in Fig. 4. The effect of an additional hole confinement is expected to be pronounced, weak, and negligible, respectively, as a result of the transition from the 2D to 3 D character of these SL's. Indeed, a good agreement of the experimental data with results of our calculation in the Kronig-Penney model with the net SL potentials (solid lines in Fig. 4) is found in the two latter SL's with a quasi-3D character. The same comparison for the 2D 60 Å/60 Å SL allows us to conclude that an additional hole confinement to the electron Coulomb potential well reduces substantially the effect of the net potential barrier heights on the exciton oscillator strength of Zeeman patterns.

Studying the oscillator strength dependence on the QW width, we have determined the ranges where the hole confinement to the net potential or to the electron Coulomb potential dominates. Analyzing the exciton parameters as a function of barrier heights altered by application of external magnetic fields in single quantum wells and superlattices, we have found a noticeable quenching of the exchange-induced effect on the exciton Zeeman splitting and oscillator strength in thick QW's and SL's with 2D character of the electron wave function. This allows us to conclude that an additional hole confinement causes a reduction of the hole wave function penetration in the barrier layers.

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