Effects of an optical phonon on excitons in quantum wells

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Effects of the polar optical phonon on excitons in quantum wells are studied theoretically by calculating binding energies, oscillator strengths, and virtual-phonon numbers involved in exciton states. It is shown that the effects depend not only on the strength of the electron-phonon coupling but also on the well width and the potential barrier: The result reflects the interrelation between the degree of the exciton confinement and the change of the polaron effects.

I. INTRODUCTION

The effects of the confinement of excitons in semiconductor quantum wells have been attracting much attention. Because of quantum size effects in these semiconductor structures a quasi-two-dimensional character appears as larger binding energies and larger oscillator strengths in the optical absorption in the case of the stronger confinement in the smaller well width.[1-6]

In various quasi-two-dimensional systems such quantum wells and heterojunctions the effects of an optical phonon on an electron, i.e., polaron effects on an electron have been studied a great deal, both experimentally[7] and theoretically.[8] A polaron in a magnetic field, for example, offers interesting information about the effective-mass correction and the resonant effect. The polaron effects on a composite particle, such as an exciton in a quantum well (QW), are expected to have a different aspect from those on an electron as in the case of the bulk. In the present work we discuss the effects of the interaction of an exciton with the longitudinal-optical (LO) phonon in a QW, i.e., the polaron effects on a QW exciton. It is well known that in bulk polar semiconductors polaron effects affect excitonic properties a great deal: the effects depend on the exciton states.[9] If the exciton radius $\langle r_n \rangle$ is much larger than the sum of the electron polaron radius R_e and the hole polaron radius R_h, both electron and hole reduce their energies by the so-called self-energy shift and the electron-hole interaction is screened by the static dielectric constant ϵ_0. In the opposite limit of $\langle r_n \rangle \ll R_e + R_h$, the polaron effects for the electron and the hole cancel because of the opposite sign of the charges of the electron and the hole, and net polaron effects become very small; the electron-hole interaction is screened by the high-frequency dielectric constant ϵ_∞.

In a QW system, the exciton radius is different from that in the bulk: the extension of the exciton in the z direction, being perpendicular to the layer, is restricted by the well width L_z, and also a shrinkage of the radius in the x-y plane occurs for smaller L_z due to the two-dimensional character.[5,6] Because of this confinement effect we may expect that polaron effects on QW excitons have a different character from those in the bulk. In the present work, we perform a model calculation of the effects and will clarify the role of the exciton–LO-phonon interaction on excitonic properties such as binding energies and oscillator strengths. In this connection, recently, there have been publications which conclude that polaron effects on the exciton binding energies in a GaAs QW are quite significant.[10,11] Our results for the effects on binding energies in a GaAs QW are not as large as those in Refs. 10 and 11, where the large polaron self-energy shifts of the electron and hole subbands are neglected.

II. CALCULATION

Let us consider a QW exciton interacting with the LO-phonon (energy $\hbar\omega$) via the Fröhlich electron-phonon interaction. The exciton consists of an electron tron (position $\mathbf{r}_e$, momentum $\mathbf{p}_e$, and mass m_e) and a hole (position $\mathbf{r}_h$, momentum $\mathbf{p}_h$, and mass m_{hz} in the z direction and m_h in the x-y plane for the ellipsoidal hole band). The Hamiltonian of the system is given by

$$H = H_{\rm ex} + H_{\rm ph} + H_i \ , \tag{1}$$

where

$$H_{\rm ex} = \frac{(P_X^2 + P_Y^2)}{2M} + \bar{H}_{\rm ex} \ , \tag{2}$$

$$\bar{H}_{\rm ex} = \frac{p_{ez}^2}{2m_e} + \frac{p_{hz}^2}{2m_{hz}} + \frac{p_x^2 + p_y^2}{2\mu} - \frac{e^2}{\epsilon_\infty r} + V_{\rm cf}^e(z_e) + V_{\rm cf}^h(z_h) \ , \tag{3}$$

$$H_{\rm ph} = \sum_q \hbar\omega a_{\mathbf{q}}^\dagger a_{\mathbf{q}} \ , \tag{4}$$

and

$$H_i = \sum_{\mathbf{q}} \hbar\omega v_q [\exp(i\mathbf{q}_\parallel \cdot \mathbf{R}_\parallel)\rho_{\mathbf{q}}(\mathbf{r}_\parallel, z_e, z_h) a_{\mathbf{q}} + \text{H.c.}] \ , \tag{5}$$

with

$$\rho_{\mathbf{q}}(\mathbf{r}_\parallel, z_e, z_h) = \exp(iq_z z_e)\exp(is_h \mathbf{q}_\parallel \cdot \mathbf{r}_\parallel) - \exp(iq_z z_h)\exp(-is_e \mathbf{q}_\parallel \cdot \mathbf{r}_\parallel) \ .$$

The first term of $H_{\rm ex}$ and the third term of $\bar{H}_{\rm ex}$ describe the kinetic energies in the x-y plane for the center-of-

mass motion [position $\mathbf{R}=(m_e\mathbf{r}_e+m_h\mathbf{r}_h)/M=(\mathbf{R}_\parallel,Z)$, momentum $\mathbf{P}=(\mathbf{P}_\parallel,P_z)$, and mass $M=m_e+m_h$] and the relative motion [position $\mathbf{r}=\mathbf{r}_e-\mathbf{r}_h=(\mathbf{r}_\parallel,z)$, momentum $\mathbf{p}=(\mathbf{p}_\parallel,p_z)$, and mass $\mu=(m_e^{-1}+m_h^{-1})^{-1}$], respectively. The confinement potential $V_{\rm cf}^j(z_j)$ ($j=e$ or h) is given by 0 for $|z_j|<L_z/2$ and V_j for $|z_j|>L_z/2$, where L_z is the well width of the QW. $a_{\mathbf{q}}^\dagger$ ($a_{\mathbf{q}}$) is the creation (annihilation) operator of the phonon with momentum $\mathbf{q}=(\mathbf{q}_\parallel,q_z)$. s_j ($j=e$ or h) is given by m_j/M. For the electron–LO-phonon interaction we use the Fröhlich interaction as in the previous work[10,11] and then $v_q=(4\pi\alpha/\Omega)^{1/2}(\hbar/2m_0\omega)^{1/4}/q$, where Ω is the volume, m_0 is the free-electron mass, and $\alpha=(\epsilon_\infty^{-1}-\epsilon_0^{-1})(m_0e^4/2\hbar^3\omega)^{1/2}$ is the dimensionless Fröhlich electron-phonon coupling constant. It is noted that the use of the present Hamiltonian means that we consider the barrier part only to yield the electronic potential barrier and thus neglect the differences in masses, dielectric constants, and phonon energies between the well part and the barrier part.

We use a variational method to treat polaron effects on excitons.[9,12] The total momentum $\hbar\mathbf{Q}_\parallel=\mathbf{P}_\parallel+\sum_{\mathbf{q}}\hbar\mathbf{q}_\parallel a_{\mathbf{q}}^\dagger a_{\mathbf{q}}$ is the constant of motion. Thus we perform the unitary transformation with the operator $U_1=\exp[i(\mathbf{Q}_\parallel-\sum_{\mathbf{q}}\mathbf{q}_\parallel a_{\mathbf{q}}^\dagger a_{\mathbf{q}})\cdot\mathbf{R}_\parallel]$ and obtain the transformed Hamiltonian $\tilde{H}=U_1^{-1}HU_1$. We set $\mathbf{Q}_\parallel=0$ (the $\mathbf{Q}_\parallel=0$ state is involved in the optical absorption) and perform the second unitary transformation with the operator $U_2=\exp[\sum_{\mathbf{q}}(F_{\mathbf{q}}^* a_{\mathbf{q}}-F_{\mathbf{q}}a_{\mathbf{q}}^\dagger)]$, where $F_{\mathbf{q}}$ is taken to be $v_q[f_{\mathbf{q}}^e\exp(-is_e\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel)-f_{\mathbf{q}}^h\exp(is_h\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel)]$. Here $f_{\mathbf{q}}^j$ ($j=e$ or h) is assumed to be real and is determined variationally later. The present choice of $F_{\mathbf{q}}$ amounts to the nonadiabatic-type approximation for motion in the $x-y$ plane and the adiabatic-type approximation for motion in the z direction: this neglects the intersubband contribution for the polaron effect and is valid when the differences among subband energies are much larger than the phonon energy. The part of the transformed Hamiltonian which does not include the phonon operator is given by

$$H_{\rm eff}=\bar{H}_{\rm ex}+\Delta V_{\rm eff}(\mathbf{r})+\Sigma_{\rm SE}\ , \tag{6}$$

where

$$\Delta V_{\rm eff}(\mathbf{r})=-\sum_{\mathbf{q}}\hbar\omega\,|\,v_q\,|^2[(e^{iq_zz_h}e^{-i\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel}+\text{c.c.})f_{\mathbf{q}}^e+(e^{iq_zz_e}e^{i\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel}+\text{c.c})f_{\mathbf{q}}^h-(e^{i\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel}+\text{c.c.})f_{\mathbf{q}}^e f_{\mathbf{q}}^h] \tag{7}$$

and $\Sigma_{\rm SE}=\Sigma_{\rm SE}^e+\Sigma_{\rm SE}^h$. Here, $\Sigma_{\rm SE}^j$ is given by

$$\Sigma_{\rm SE}^j=\sum_{\mathbf{q}}\hbar\omega\,|\,v_q\,|^2[(1+R_j^2q_\parallel^2)f_{\mathbf{q}}^j-(e^{iq_zz_j}+\text{c.c.})]f_{\mathbf{q}}^j\ , \tag{8}$$

where the polaron radius $R_j=(\hbar/2m_j\omega)^{1/2}$. The following variational wave function for an exciton is chosen:[13–15]

$$\Phi_n\,|\,0\rangle=N_n\psi_e(z_e)\psi_h(z_h)\phi_n(\mathbf{r}_\parallel)\,|\,0\rangle\ , \tag{9}$$

where $\psi_j(z_j)$ is the subband wave function for an electron ($j=e$) or a hole ($j=h$). $\phi_n(\mathbf{r}_\parallel)$ describes the relative motion in the x-y plane, N_n is the normalization factor, and $|\,0\rangle$ is the phonon vacuum state. Then the variational condition $\delta\langle\Phi_n,0\,|\,H_{\rm eff}\,|\,\Phi_n,0\rangle/\delta f_{\mathbf{q}}^j=0$ determines the form of $f_{\mathbf{q}}^f$ as

$$f_{\mathbf{q}}^j=\frac{(\rho_{q_z}^j-\bar{\rho}_{\mathbf{q}}^{j'})(1+R_j^2q_\parallel^2)+(\rho_{q_z}^{j'}-\bar{\rho}_{\mathbf{q}}^{j})\rho_{q_\parallel}^\parallel}{(1+R_j^2q_\parallel^2)(1+R_{j'}^2q_\parallel^2)-(\rho_{q_\parallel}^\parallel)^2}\ ,\qquad j\neq j'=e,h\ , \tag{10}$$

where

$$\rho_{q_\parallel}^\parallel=\langle\Phi_n\,|\,\cos(\mathbf{q}_\parallel\cdot\mathbf{r}_\parallel)\,|\,\Phi_n\rangle\ ,$$

$$\rho_{q_z}^j=\langle\Phi_n\,|\,\cos(q_zz_j)\,|\,\Phi_n\rangle\ ,$$

and $\bar{\rho}_{\mathbf{q}}^{\,j}=\rho_{q_\parallel}^\parallel\rho_{q_z}^j$. Thus with use of Eqs. (6)–(10) the nth exciton energy can be calculated from

$$E_n=\langle\Phi_n\,|\,H_{\rm eff}\,|\,\Phi_n\rangle\ , \tag{11}$$

if the wave function Φ_n is known. It is noted that the exciton energy without polaron effects can be calculated from $E_n=\langle\Phi_n\,|\,\bar{H}_{\rm ex}\,|\,\Phi_n\rangle$. Also we note that the usual calculation for the QW exciton uses the static dielectric constant ϵ_0 for the screening of the electron-hole interaction, i.e., uses $E_n=\langle\Phi_n\,|\,\bar{H}_{\rm ex}\,|\,\Phi_n\rangle$ with the replacement of ϵ_∞ by ϵ_0.[14] This assumes that the LO phonon can follow the exciton motion completely, which is valid in the very-shallow-exciton case.

Here we consider the lowest ionized exciton state (or the exciton state in the shallow limit) for which $\rho_{q_\parallel}^\parallel$ becomes zero. In this case

$$f_q^j=\rho_{q_z}^j/(1+R_j^2q_\parallel^2)$$

and

$$\Sigma_{\rm SE}^j=-\sum_{\mathbf{q}}\hbar\omega\,|\,v_q\,|^2[2\cos(q_zz_j)-\rho_{q_z^j}]f_q^j\ .$$

Then the energy of the lowest ionized exciton E_∞ can be calculated from $E_\infty=E^e+E^h$, where

$$E^j=[\langle\psi_j\,|\,p_{jz}^2/2m_{jz}+V_{\rm cf}(z_j)+\Sigma_{\rm SE}^j\,|\,\psi_j\rangle]\qquad(j=e,h)\ . \tag{12}$$

Here

$$\langle\psi_j\,|\,\Sigma_{\rm SE}^j\,|\,\psi_j\rangle=-\sum_{\mathbf{q}}\hbar\omega\,|\,v_q\,|^2\,|\,\rho_{q_z^j}^j\,|^2/(1+R_j^2q_\parallel^2)$$

is the contribution due to the polaron self-energy effect and can be also derived from second-order perturbation theory for the electron (hole) state $\psi_j(z_j)e^{i\mathbf{k}_\parallel\cdot\mathbf{r}_{\parallel j}}$ with only the intrasubband contribution. Thus, actually, the ener-

gy E^e (E^h) and the wave function $\psi_e(z_e)$ [$\psi_h(z_h)$] are those for the electron (hole) subbands. In order to calculate E^j and ψ_j, we choose the following variational subband wave function for the lowest subband state:

$$\psi_j(z_j)=\begin{cases} N_j \cos(k_j z_j) & \text{for } |z_j| < L_z/2 \\ N_j C_j \exp(-\gamma_j |z_j|) & \text{for } |z_j| > L_z/2 \end{cases}, \quad (13)$$

with $C_j=\cos(k_j L_z/2)\exp(\gamma_j L_z/2)$ and $\gamma_j=(2m_j V_j/\hbar^2-k_j^2)^{1/2}$. Here N_j is the normalized constant. Taking k_j as a variational parameter and minimizing E^j in (12), we obtain the subband energy E^j and wave function ψ_j which include the polaron effect. It is noted that the energy shift of the subband state $\bar{\Sigma}^j_{\rm SE}$, due to the polaron effect, is given by the difference of E^j with and without the polaron self-energy term $\Sigma^j_{\rm SE}$.

Now, after determining the subband state, we calculate the $1s$ exciton state variationally. Using the $1s$-type wave function $\phi_{1s}(\mathbf{r}_\parallel)=\exp(-\alpha_{1s} r_\parallel)$ and determining the parameter α_{1s} from the minimization of E_{1s} in (11), we obtain the exciton energy E_{1s} and then the binding energy of the $1s$ exciton from

$$E^B_{1s}=E^e+E^h-E_{1s} . \quad (14)$$

The oscillator strength of the zero-phonon state of the $1s$ exciton is calculated in the usual way:[9,16]

$$f_{1s}=B^b |\phi_{1s}(0)|^2 (N^2_{1s}/L_z) F(0)^2 e^{-g_{1s}} , \quad (15)$$

where

$$B^b=2|M_{\rm CV}|^2/m_0\hbar\omega ,$$

$$F(0)=\left| \int dz\, \psi_e(z)\psi_h(z) \right|^2$$

and

$$g_{1s}=\sum_{\mathbf{q}} |v_q|^2 |f^e_{\mathbf{q}}-f^h_{\mathbf{q}}|^2 .$$

Here $M_{\rm CV}$ is the interband matrix element and $\hbar\omega$ is the photon energy involved in the optical transition. Also, the oscillator strengths of one- and two-phonon states are given by $f_{1s}g_{1s}$ and $f_{1s}g^2_{1s}/2$, respectively, and thus g_{1s} governs the strengths of phonon side bands. In order to see the largeness of the polaron effects, the virtual-phonon number involved in the exciton state, $\langle N_{\rm ph}\rangle$, is calculated from

$$\langle N_{\rm ph}\rangle=\left\langle \Psi_n \left| \sum_{\mathbf{q}} a^\dagger_{\mathbf{q}} a_{\mathbf{q}} \right| \Psi_n \right\rangle , \quad (16)$$

where $\Psi_n=U_1 U_2 |\Phi_n,0\rangle$.

Numerical calculation is performed for the lowest heavy-hole excitons in two types of materials. One is the GaAs QW, being a typical III-V compound, in the finite-potential-barrier (FPB) model and in the infinite-potential-barrier (IPB) model and the other is the ZnSe QW, being a typical II-VI compound, in the infinite-potential-barrier model. Material parameters used in the calculation are as follows: $m_e/m_0=0.067$ (0.160), $m_{hz}/m_0=0.353$ (0.755), $m_h/m_0=0.090$ (0.200), $\epsilon_\infty=10.9$ (5.6), $\epsilon_0=12.9$ (8.7), and $\hbar\omega=36.2$ (38.6) meV for GaAs (ZnSe). For the finite-potential-barrier part in a GaAs QW, we choose $Al_{0.3}Ga_{0.7}As$: values of the potential barrier $V_e=228$ meV and $V_h=152$ meV are used. It is noted that values of the dimensionless Fröhlich electron-phonon coupling α are 0.275 for a GaAs QW and 1.324 for a ZnSe QW, and thus electron-phonon coupling in GaAs is rather weak. Calculated results are shown in Figs. 1–6 and are discussed in the next section.

III. DISCUSSION

First we discuss the results for a GaAs QW, i.e., the GaAs-$Al_{0.3}Ga_{0.7}As$ QW in the FPB model and GaAs QW in the IPB model. Figure 1 shows a diagram of the energy E_{1s} for the $1s$ exciton and the energy $E_\infty=E^e+E^h$ for the lowest ionized exciton in a GaAs-$Al_{0.3}Ga_{0.7}As$ QW. With polaron effects, both E_{1s} and E_∞ change their energies as seen in Fig. 1. Because the energy shift for E_∞ is larger than that for E_{1s}, the resulting binding energy E^B_{1s} becomes smaller by the inclusion of polaron effects. Binding energy as a function of the well width L_z in a GaAs QW is plotted in Fig. 2. Results of the simpler calculation, i.e., those from the Hamiltonian $\bar{H}_{\rm ex}$ itself and $\bar{H}_{\rm ex}$ with the replacement of ϵ_∞ by ϵ_0 are also shown. The results with detailed polaron effects deviate only by (at most) several percent from those of the simpler calculation with the static dielectric constant $\epsilon=\epsilon_0$, which has been performed usually.[14] This result is due to the smaller exciton-phonon coupling and the shallowness of the exciton in a GaAs QW as seen in the relation of $E^B_{1s} \ll \hbar\omega$. In a GaAs-$Al_{0.3}Ga_{0.7}As$ QW for the very much smaller well width L_z, the effect of the exciton confinement becomes smaller and then excitons have a large amplitude in the barrier region, which brings the decrease of the binding energy as seen in Fig. 2.[14] We see also the change of the oscillator strength due to polaron effects in Fig. 3. Effects seem to be a bit larger compared

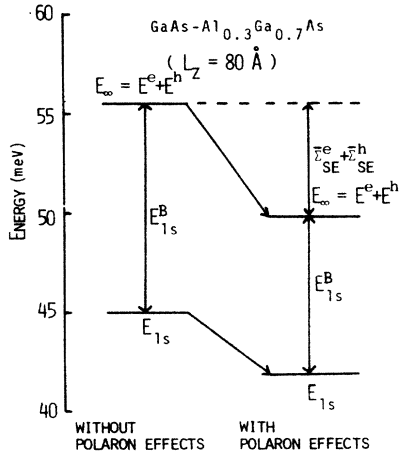

FIG. 1. Energy diagram with and without polaron effects for the $1s$ exciton and the lowest ionized exciton, confined in a GaAs-$Al_{0.3}Ga_{0.7}As$ finite-potential-barrier QW with the well width $L_z=80$ Å.

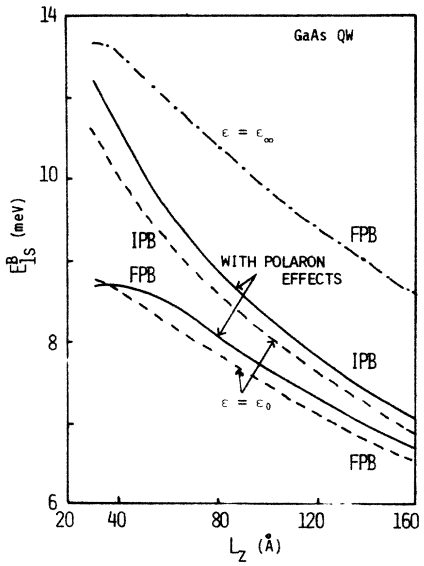

FIG. 2. Binding energy E^B_{1s} of excitons as a function of the well width L_z, confined in a GaAs QW: the GaAs-$Al_{0.3}Ga_{0.7}As$ QW in the finite-potential-barrier (FPB) model and GaAs QW in the infinite-potential-barrier (IPB) model. Solid lines show the result by the detailed calculation of polaron effects. Dashed lines and dot-dashed lines show the results of the simpler calculation with the effective dielectric constant $\epsilon=\epsilon_0$ and $\epsilon=\epsilon_\infty$, respectively.

to those for the binding energy. We note that calculated values of g_{1s} are rather small: 4.9×10^{-3} (1.4×10^{-3}) at $L_z=40$ (80) Å for a GaAs-$Al_{0.3}Ga_{0.7}As$ QW. This means that phonon sidebands of the $1s$ excitons in a GaAs QW are rather small compared to the zero-phonon lines. When the well width L_z decreases, the average virtual-phonon number $\langle N_{ph}\rangle$ for the $1s$ exciton in Fig. 4 changes very little, while $\langle N_{ph}\rangle$ for the lowest ionized exciton increases. This different behavior reflects the interrelation between the exciton confinement and the polaron effects: in the x-y plane, the $1s$ exciton shrinks while the lowest ionized exciton does not, when the well width becomes small.

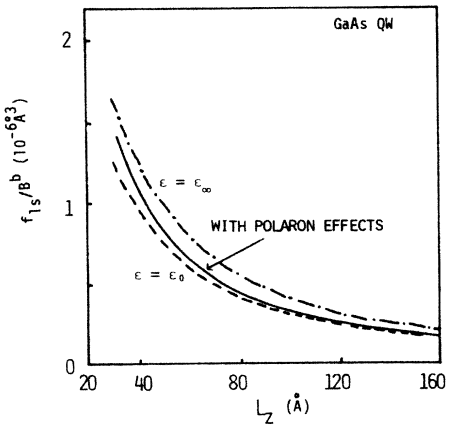

FIG. 3. Oscillator strength f_{1s}/B^b as a function of the well width L_z in a GaAs-$Al_{0.3}Ga_{0.7}As$ QW with a FPB. Results are due to the calculations with detailed polaron effects and the simpler choice of $\epsilon=\epsilon_\infty$ and $\epsilon=\epsilon_0$ as in Fig. 2.

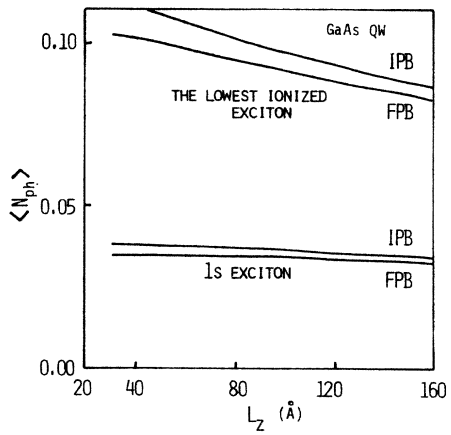

FIG. 4. Average virtual-phonon number $\langle N_n\rangle$ as a function of the well width L_z for the $1s$ exciton and the lowest ionized exciton in a GaAs QW: the GaAs-$Al_{0.3}Ga_{0.7}As$ QW in the FBP model and the GaAs QW in the IPB model.

Here we note the recent publications by Erçelebi-Özdinger and Degani-Hipólito.[10,11] They calculated the $1s$ exciton energy E_{1s} with the inclusion of polaron effects by the adiabatic method. The adiabatic method yields the zero-energy shifts $\bar{\Sigma}^j_{SE}$ for the lowest ionized exciton. Then, using the lowest ionized exciton energy $E_\infty=E^e+E^h$ without the polaron self-energy effect, they calculated the exciton binding energy E^B_{1s} and concluded that polaron effects yield much larger binding energies compared to those of the usual simpler calculation with $\epsilon=\epsilon_0$. As seen in Fig. 1, $\bar{\Sigma}^e_{SE}+\bar{\Sigma}^h_{SE}$ is large and needs to be taken into account. This fault is also applied to the very recent work on the exciton binding energy of the quantum well wire.[17] In passing it is noted that the present nonadiabatic-type calculation for the motion in the x-y plane is more suitable to the semiconductor QW than the adiabatic calculation: in a GaAs-$Al_{0.3}Ga_{0.7}As$ QW the present nonadiabatic method yields lower energies by 3.2 (3.1) meV at $L_z=40$ (80) Å than the adiabatic method. The importance of the polaron self-energy effect also appears in the bound polaron problem in a QW: this has been clearly shown by Mason and Das Sarma in their effective-mass approach to obtain the binding energy.[18] On the other hand, some papers missed the polaron self-energy effect and concluded that polaron effects yield the large binding energy.[19,20]

On the binding energy of the lowest heavy-hole exciton in a GaAs QW, magnetooptical experiment and photoluminescence experiments offer some information.[1-4] The recent results of Refs. 3 and 4 agree reasonably well with those of the theoretical calculation with valence-band coupling and without detailed polaron effects:[21,22] valence-band coupling effectively increases the heavy-hole mass and thus produces larger exciton binding energy. The present model calculation, whose purpose is to discuss the role of the polaron effects on excitonic proper-

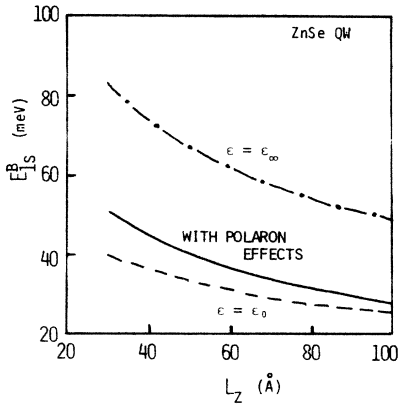

FIG. 5. Binding energy as a function of the well width L_z in a ZnSe QW with the IPB. Results are due to the calculations with the detailed polaron effects and the simpler choice of $\epsilon=\epsilon_\infty$ and $\epsilon=\epsilon_0$.

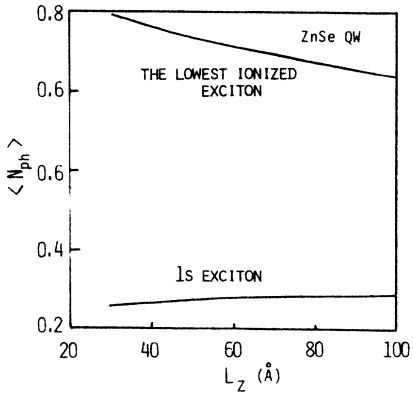

FIG. 6. Average virtual-phonon number $\langle N_n \rangle$ as a function of the well width L_z for the 1s exciton and the lowest ionized exciton, confined in a ZnSe QW with the IPB.

ties, uses the hole-mass value $m_h=0.090m_0$ by neglecting the valence-band coupling: the binding energies obtained are smaller than experimental values by 10–20%. Both the valence-band coupling effect and the detailed polaron effects increase exciton binding energies in a GaAs QW, though the latter effect is smaller.

Next we discuss the results of the ZnSe QW in the IPB model. Figure 5 and Fig. 6 show the binding energy E^B_{1s} and the virtual-phonon number $\langle N_{ph} \rangle$ as functions of the well width L_z. We see in Fig. 5 that, when the well width becomes small, E^B_{1s} with detailed polaron effects deviates much from that with $\epsilon=\epsilon_0$ and becomes closer to that with $\epsilon=\epsilon_\infty$. This means that the larger cancellation of polaron effects for an electron and a hole for the 1s exciton occurs for the smaller well width L_z, because of the confinement in the z direction and the shrinkage of the exciton radius in the x-y plane. The cancellation is clearly seen in Fig. 6 where the virtual-phonon number $\langle N_{ph} \rangle$ for the 1s state decreases for the smaller L_z. This behavior is rather different from that in Fig. 2 and Fig. 4: this is due to the larger electron-phonon coupling for ZnSe compared to that for GaAs, as mentioned in Sec. II. The result indicates that polaron effects in a QW depend sensitively not only on the potential barrier and the well width of the QW but also on the strength of the electron-phonon coupling.

IV. SUMMARY

We have performed a model calculation of polaron effects for QW excitons. It has been found that polaron effects in a QW system have a rather different character from those in the bulk, reflecting the exciton confinement effect: the potential barrier and the well width as well as the strength of the electron-phonon coupling affect excitonic properties of the binding energies and the oscillator strengths. For materials with stronger electron-phonon coupling such as I-VII compounds (like cuprous halides and alkali-metal halides), the effect will be much larger. In the present work we take account of only the intrasubband contribution of the polaron effects for motion in the z direction. In a quantitatively better calculation the intersubband contribution among electron subbands and heavy (light)-hole subbands, based on valence-band coupling, needs to be considered. Also, for a better calculation it is necessary to consider the effects of the interface phonon and the form of the electron-phonon interaction suitable to various QW systems.[23,24] These are the problems to be considered in the future.

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