Effect of Exciton-Longitudinal Optical Phonon Interaction on Exciton Binding Energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ Single Quantum Wells

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We study the effect of the exciton-longitudinal optical (LO) phonon interaction on the exciton binding energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ single quantum wells (SQWs) for the Cd alloy content (x) range 0.1–0.3. The heavy- and light-hole exciton binding energies increase with the exciton-LO phonon interaction. The increase in the maximum heavy-hole (light-hole) exciton binding energy for $x = 0.3$ is 9.1 meV (4.9 meV). In narrow $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs, the heavy-hole exciton binding energy calculated by taking into account the exciton-LO phonon interaction for values of x in the range 0.1–0.3 exceed the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$.

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I. INTRODUCTION

$\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ quantum wells (QWs) have been experimentally studied for their use in the fabrication of UV optoelectronic devices [1–3]. The exciton binding energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ single quantum wells (SQWs) are greater than the room-temperature (RT) thermal energy [4]. If the excitons are stable at RT, exciton transitions can be used to generate light in light-emitting devices. For this purpose, a large exciton binding energy is required.

Strong interactions between excitons and longitudinal optical (LO) phonons usually lead to the dissociation of the excitons at RT. Therefore, suppression of exciton-LO phonon scattering is important. The dissociation of excitons should be prevented in QWs, where the excitons have a greater energy than LO phonons. In the case of ZnS, the bulk exciton binding energy (36 meV) is lower than the LO-phonon energy (44 meV); hence, exciton-LO-phonon scattering can be suppressed in ZnS-based QWs, where the exciton binding energy is usually enhanced by a factor of 1.5–2 because of quantum confinement.

In a previous study [4], we calculated the exciton binding energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ QWs; to simplify the calculations, we ignored the effect of exciton-LO phonon interaction on the electron-hole Coulomb interactions. Senger and Bajaj reported that the exciton binding energies calculated for QWs increase when the effect of the exciton-LO phonon interaction is considered [5]. They calculated the exciton binding energies for various II-VI semiconductor QWs while taking into account the effect of the exciton-LO phonon interaction [5, 6]. The results of their calculations showed that the effect of exciton-LO phonon interaction on electron-hole Coulomb interactions plays an important role in increasing the exciton binding en-

ergy in II-VI semiconductor QWs [5, 6].

To investigate the increase in the exciton binding energy caused by the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ QWs, we theoretically calculate the heavy- and light-hole exciton binding energies by taking into account the effect of the abovementioned interaction at RT.

II. CALCULATION METHODS

Senger and Bajaj have reported a detailed method for calculating the exciton binding energies in QWs wherein the effect of electron-LO phonon interaction was considered [5]. The exciton Hamiltonian [5] is given as

$$H = -\frac{\hbar^2}{2\mu_{\pm}} \frac{1}{\rho} \frac{\partial}{\partial \rho} \rho \frac{\partial}{\partial \rho} - \frac{\hbar^2}{2m_e^*} \frac{\partial^2}{\partial z_e^2} - \frac{\hbar^2}{2m_{\pm}} \frac{\partial^2}{\partial z_h^2} + V_e(z_e) + V_h(z_h) + V_{PB} + E_{self} + V_{KT}, \quad (1)$$

where $\mu_{\pm}$ is the reduced mass of the exciton. The value of $\mu_{\pm}$ [7] is given by

$$\frac{1}{\mu_{\pm}} = \frac{1}{m_e^*} + \frac{1}{m_0} (\gamma_1 \pm \gamma_2), \quad (2)$$

where m_0 is the free-electron mass and m_e^* is the electron effective mass. The quantity $m_{\pm}$ is the hole effective mass [7] and is given by

$$\frac{1}{m_{\pm}} = \frac{1}{m_0} (\gamma_1 \mp 2\gamma_2). \quad (3)$$

To simplify our calculations, the effective masses of the electron, heavy-hole, and light-hole are assumed to be position independent; further, their effective masses are assumed to be equal to those of the electrons, heavy-holes, and light-holes in $\text{Cd}_x\text{Zn}_{1-x}\text{S}$. The $V_e(z_e)$ and $V_h(z_h)$ are given by [7]

$$V_e(z_e) = \begin{cases} 0 & (|z_e| \leq L_w/2) \\ V_e & (|z_e| > L_w/2) \end{cases}, \quad (4)$$

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and

$$V_h(z_h) = \begin{cases} 0 & (|z_h| \leq L_w/2) \\ V_{hh} \text{ or } V_{lh} & (|z_h| > L_w/2) \end{cases} \quad (5)$$

Here, V_e , V_{hh} , and V_{lh} are the conduction, heavy-hole and light-hole band offsets, respectively, and L_w is the well width. Here, we define the origin of the coordinate system at the center of the well layer. [7]

Band offsets are calculated by using the “model-solid approach” [8]. The heavy-hole band offset V_{hh} (light-hole band offset V_{lh}) is calculated as the difference between the energies at the top of the heavy-hole (light-hole) bands in $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and ZnS , and the conduction band offset V_e is calculated as the difference between the energies at the bottom of the conduction bands in $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and ZnS .

The energy at the top of the valence band in unstrained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ is calculated by linear interpolation without using a bowing parameter. On the other hand, the energy at the bottom of the conduction band in unstrained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ is calculated by linear interpolation using a bowing parameter. In $\text{Cd}_x\text{Zn}_{1-x}\text{S}$, the cations (Cd and Zn) have a strong influence on the conduction band, whereas S anions determine the energy at the top of the valence band. Therefore, the effect of bandgap bowing is taken into account when calculating the energy at the bottom of the conduction band.

The energy at the top of the heavy-hole (light-hole) band in strained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ is defined as the summation of the energy at the top of the valence band in unstrained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and the energy shift of the heavy-hole (light-hole) band in strained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$. On the other hand, the energy at the bottom of the conduction band in strained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ is defined as the summation of the energy at the bottom of the conduction band in unstrained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and the energy shift of the conduction band in strained $\text{Cd}_x\text{Zn}_{1-x}\text{S}$.

The following relations are used to describe the energy shifts of the strained conduction (dE_c), heavy-hole (dE_{hh}), and light-hole (dE_{lh}) bands [9]:

$$\varepsilon = \frac{a_b - a_w}{a_w}, \quad (6)$$

$$\varepsilon_{zz} = -\frac{2C_{12}}{C_{11}}\varepsilon, \quad (7)$$

$$E_S = -b(\varepsilon_{zz} - \varepsilon), \quad (8)$$

$$E_H = a_v(2\varepsilon + \varepsilon_{zz}), \quad (9)$$

$$dE_c = a_c(2\varepsilon + \varepsilon_{zz}), \quad (10)$$

$$dE_{hh} = E_H + E_S, \quad (11)$$

$$dE_{lh} = E_H - \frac{\Delta_{so}}{2}(1+x) + \frac{\Delta_{so}}{2}(1-2x+9x^2)^{1/2}, \quad (12)$$

where a_w and a_b are the lattice constants of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells and ZnS barriers, respectively. ε is the in-plane strain (x - y plane), ε_{zz} is the perpendicular

strain (z direction), and C_{ij} is the elastic stiffness constant. $x = E_S/\Delta_{so}$, where Δ_{so} is the spin-orbit splitting energy. a_v and a_c are the hydrostatic deformation potentials in the valence and conduction bands, respectively, and b is the shear deformation potential.

The effect of exciton-LO phonon interaction is described by the effective potential V_{PB} between an electron and a hole (PB potential) with a self-energy term E_{self} , which was derived from the exciton-LO phonon Hamiltonian by Pollmann and Büttner [10]. The PB potential and the self-energy terms are given as [5]

$$V_{PB} = -\frac{e^2}{\epsilon_s r} - \frac{e^2}{\epsilon^* r} \left[\frac{C^4}{B^4} - \frac{m_e^* h_e}{\Delta m} e^{-\frac{r A_e}{R_e}} + \frac{m_h^* h_h}{\Delta m} e^{-\frac{r A_h}{R_h}} - \left(h_\mu + \frac{C^3 r}{2B^3 a_{ex}} \right) e^{-\frac{r B}{R_\mu}} \right], \quad (13)$$

$$E_{self} = -(\alpha_e g_e + \alpha_h g_h - \alpha_\mu g_\mu) \hbar \omega_{LO}, \quad (14)$$

where $r = \sqrt{\rho^2 + (z_e - z_h)^2}$, $\epsilon^* = (1/\epsilon_\infty - 1/\epsilon_s)^{-1}$, and ϵ_s and ϵ_∞ are the static and optical dielectric constants for the well, respectively. $\Delta m = m_h^* - m_e^*$ is the mass difference. $M = m_h^* + m_e^*$ is the total mass of the exciton. a_{ex} is the exciton size, and $\hbar \omega_{LO}$ is the LO phonon energy. The material parameters appearing in expression for calculating the PB potential are taken as those of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well [5]. The value of the hole mass is taken as $m_h^* = 1/\gamma_1$. For a more realistic understanding of the exciton binding energy calculated by taking into account the effect of the PB potential, an understanding of the effect of the independent hole masses on the PB potential is necessary. The acquisition of this understanding is not an easy task. To simplify our calculations, we use the weighted average of the hole masses for determining the PB potential. Reference 5 provides the details of the method for calculating the a_{ex} , dimensionless charge-phonon coupling constants (α_e , α_h , and α_μ), characteristic polaron radii for the electron, hole, and excitons with reduced masses (R_e , R_h , and R_μ), and remaining coefficients (A_e , A_h , B , C , h_e , h_h , h_μ , g_e , g_h , and g_μ). Details of the method for calculating the exciton binding energies by taking into account the effect of the exciton-LO phonon interaction are also provided in Ref. 5.

To account for the effect of dielectric confinement on the electron-hole Coulomb interaction, we use the effective potential term V_{KT} which was defined by Kumagai and Takagahara (KT) in the image-charge method [11]. The expression for the abovementioned potential term is given in the form of an infinite series. For example, when the electron and holes are in the well, V_{KT} is expressed as [12]

$$V_{KT} = - \sum_{n=-\infty}^{\infty} \frac{\xi^{|n|}}{\epsilon_s \sqrt{\rho^2 + (z_e - (-1)^n z_h + nL_w)^2}}, \quad (15)$$

where $\xi = (\epsilon_s^w - \epsilon_s^b)/(\epsilon_s^w + \epsilon_s^b)$. ϵ_s^w and ϵ_s^b are the static dielectric constants for the well and the barrier, respectively. Reference 11 contains the details of the method for calculating the exciton binding energies by taking into account the effect of dielectric confinement on the electron-hole Coulomb interaction.

To calculate the ground-state energies of the heavy- and light-hole excitons, we minimize the expectation values of the Hamiltonian calculated using a trial function with

two variational parameters [5]. The trial function [5] is expressed as

$$\varphi(z_e, z_h, \rho) = \phi_e(z_e)\phi_h(z_h) \exp \left\{ -\alpha [\rho^2 + \beta (z_e - z_h)^2]^{1/2} \right\}, \quad (16)$$

with

$$\phi_e(z_e) = \begin{cases} B_e \exp(-\lambda_e z_e) & (|z_e| \leq L_w/2) \\ \cos(k_e z_e) & (|z_e| > L_w/2) \end{cases}, \quad (17)$$

$$\phi_h(z_h) = \begin{cases} B_h \exp(-\lambda_h z_h) & (|z_h| \leq L_w/2) \\ \cos(k_h z_h) & (|z_h| > L_w/2) \end{cases}, \quad (18)$$

where $\phi_e(z_e)$ and $\phi_h(z_h)$ are the electron and hole wave functions, respectively. $\phi_e(z_e)$ and $\phi_h(z_h)$ are taken to be the lowest subband-energy solutions for finite square-well potentials [7]. The electron and hole subband energies are determined by numerically solving the equation for finite square potential wells. B_e , B_h , λ_e , λ_h , k_e , and k_h are obtained using the interface conditions between the well and barrier layers. α and β are the variational parameters.

The heavy-hole exciton transition energy is determined by subtracting the heavy-hole exciton binding energy from the effective heavy-hole bandgap energy; the effective heavy-hole bandgap energy is calculated by the summation of the minimum conduction subband energy, minimum heavy-hole subband energy, and heavy-hole bandgap energy of the well layer. The light-hole exciton transition energy is calculated in a corresponding similar.

Here, we assume that the barrier width in ZnS is considerably larger than the critical thickness of the barrier layer; therefore, the lattice constant of the ZnS barrier approaches the bulk value. We also assume that the lattice constant of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ is equal to that of ZnS when the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well is sandwiched between two ZnS barriers. Under these conditions, we calculate the critical thickness of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well in ZnS by using Matthews and Blakeslee's (MB's) mechanical equilibrium model [13]. The critical thickness h_c is given by

$$h_c = \frac{b(1 - \nu \cos^2 \alpha)}{2\pi f(1 + \nu) \cos \lambda} \left(\ln \frac{h_c}{b} + 1 \right), \quad (19)$$

where ν is the Poisson's ratio; f , the lattice mismatch between $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and ZnS; and b , the Burgers vector. Here, we assume that $b = \sqrt{2}a$, $\cos \alpha = 0$, and $\cos \lambda = 1$ where an edge dislocation is assumed for the critical thickness calculation; a is the lattice constant of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well.

III. RESULTS AND DISCUSSION

The physical parameters used for our calculations are listed in Table I. The parameters corresponding to the alloy material are derived by linear interpolation. We calculate the critical thickness h_c of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well in ZnS when x is in the range 0.1–0.5. Figure 1 shows the calculated results. It is apparent that h_c decreases with an increase in x . The h_c values corresponding to $x = 0.05$ and $x = 0.5$ differ by approximately two orders of magnitude. For calculating the heavy- and light-hole exciton binding

FIG. 1: Critical thickness h_c of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ in ZnS as a function of x . The closed circles indicate the calculated values. The solid line is a guide for the eye.

FIG. 2: V_e , V_{hh} , and V_{lh} as functions of x in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs. The closed squares, triangles, and circles indicate the calculated V_e , V_{hh} , and V_{lh} values, respectively. The solid lines are a guide for the eye.

energies, the thicknesses of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells for $x = 0.1$, 0.2, and 0.3 are taken as 40 nm, 30 nm, and 10 nm, respectively.

We calculate V_e , V_{hh} , and V_{lh} as functions of x in the $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for values of x in the range 0.1–0.3. Figure 2 shows the calculated results. V_e , V_{hh} , and V_{lh} increase with x because the difference in bandgap between $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ and ZnS increases with x . V_{hh} is greater than V_{lh} because of the induced compressive strain. In this system, the lattice constant of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells is greater than that of the ZnS barriers. As a result, compressive strain is induced in the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells.

We calculate the heavy- and light-hole exciton bind-

TABLE I: Physical parameters used in calculations.

	CdS	ZnS
Lattice constant, a (nm)	0.5832 [14]	0.54093 [15]
Bandgap energy at RT, E_g (eV)	2.36 [16]	3.68 [17]
Energy at the top of the valence band, E_{v0} (eV)	-11.68 [18]	-11.84 [18]
Hydrostatic deformation potential in conduction band, a_c (eV)	-3.59 [19]	-2.78 [15]
Hydrostatic deformation potential in valence band, a_v (eV)	1.51 [19]	1.2 [15]
Shear deformation potential, b (eV)	-0.5 [19]	-0.7 [15]
Elastic stiffness constant, C_{11} (GPa)	78 [15]	106.7 [15]
Elastic stiffness constant, C_{12} (GPa)	53 [15]	66.6 [15]
Spin-orbit splitting energy, Δ_{so} (eV)	0.07 [20]	0.072 [15]
Effective mass of the electron, m_e (m_0)	0.173 [19]	0.28 [21]
Luttinger parameter, γ_1	2.2 [19]	2.54 [21]
Luttinger parameter, γ_2	0.35 [19]	0.75 [21]
Static dielectric constant, ϵ_s (ϵ_0)	9.12 [17]	8.9 [6]
Optical dielectric constant, ϵ_∞ (ϵ_0)	5.32 [17]	5.1 [22]
LO phonon energy, $\hbar\omega_{LO}$ (meV)	37 [23]	44 [6]
Bowing parameter for $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ (eV)		0.3 [24]

FIG. 3: (a) Heavy-hole and (b) light-hole exciton binding energies calculated by neglecting (broken lines) and considering (solid lines) the effect of the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs as functions of well width for $x = 0.1, 0.2$, and 0.3 .

ing energies both by ignoring [ignoring the V_{PB} , E_{self} , and V_{KT} in eq. (1)] and considering [using the whole of eq. (1)] the effect of the exciton-LO phonon interaction. Figures 3(a) and (b) show the heavy- and light-hole exciton binding energies calculated both by considering and ignoring the effect of the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs, respectively, for $x = 0.1, 0.2$, and 0.3 . A comparison of the results of our calculations with the experimental results is indispensable for checking the reliability of our calculations, but the experimental results for the heavy- and light-hole exciton binding energies are not available at present. However, the exciton binding energy calculated using the PB potential of ZnS/ZnMgS QWs was in relatively good agreement with the exciton binding energy measured for narrow ZnS/ZnMgS QWs [6].

As L_w decreases, the heavy- and light-hole exciton

binding energies increase to a maximum and then decrease rapidly. This is because when the L_w decreases, the exciton wave function is compressed in the wells and extends to the barrier region. [7] The shape of the curve illustrating the dependence of the heavy- and light-hole exciton binding energies on L_w is consistent with that reported by Greene *et al.* [7]. The changes in the binding energies of the heavy- and light-hole excitons with L_w are essentially similar. The heavy-hole (light-hole) exciton binding energy calculated by ignoring the effect of the exciton-LO phonon interaction increases with x , reaching a value of 45.2 meV (36.3 meV) at $x = 0.3$. The light-hole exciton binding energy is lower than the heavy-hole exciton binding energy because the value of V_h is smaller than that of V_{hh} . This indicates that the degree of compression of the exciton wave function for a heavy-hole exciton is greater than that for a light-hole exciton.

The heavy-hole (light-hole) exciton binding energy calculated by considering the effect of the exciton-LO phonon interaction increases with x , reaching a value of 56.2 meV (42.8 meV) at $x = 0.3$. The value of L_w at which the exciton binding energy is maximum decreases with an increase in x because both the conduction (V_e) and valence (V_{hh} or V_{lh}) band offsets increase with x . The shape of the curve illustrating the dependence of the heavy- and light-hole exciton binding energies on L_w remains the same, irrespective of whether the effect of the exciton-LO phonon interaction is considered or ignored. Table II shows the increases in the maximum heavy-hole and light-hole exciton binding energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.1, 0.2$, and 0.3 . The maximum heavy-hole (light-hole) exciton binding energy calculated by considering the effect of the exciton-LO phonon interaction increases with x , reaching a value of 9.1 meV (4.9 meV) at $x = 0.3$.

The exciton binding energies of $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.1, 0.2$, and 0.3 are greater than RT thermal energy (about 25 meV). As a result, the interactions between excitons and LO phonons usually lead to the dissociation of the excitons at RT. Therefore, we compared the exciton binding energies and the LO phonon energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.1, 0.2$, and 0.3 . The LO phonon energies of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ for $x = 0.1, 0.2$, and 0.3 are 43.3, 42.6, and 41.9 meV, respectively. The heavy-hole ex-

TABLE II: Increase in maximum heavy- and light-hole exciton binding energies (meV) and the L_w values for the maximum heavy-hole (light-hole) exciton binding energy (nm).

	$x = 0.1$	$x = 0.2$	$x = 0.3$
Heavy-hole	8.9	9.1	9.1
L_w for heavy-hole	4.0	2.0	1.8
Light-hole	5.3	5.1	4.9
L_w for light-hole	9.0	7.0	5.0

citon binding energies calculated by ignoring the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.1, 0.2$, and 0.3 are lower than the LO phonon energies of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ for $x = 0.1, 0.2$, and 0.3 , respectively. The heavy-hole exciton binding energy calculated by ignoring the exciton-LO phonon interaction for $x = 0.3$ is higher than the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells when the well width is in the range 1.0–3.0 nm. For all x , the maximum light-hole exciton binding energies calculated by ignoring the effect of the exciton-LO phonon interaction are lower than the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells. The heavy-hole exciton binding energies calculated by considering the effect of the exciton-LO phonon interaction for $x = 0.1, 0.2$, and 0.3 are higher than the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells when the well widths are in the ranges of 1.4–11.0, 0.7–12.0, and 0.5–10.0 nm, respectively. The light-hole exciton binding energies calculated by considering the effect of the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.1$ and 0.2 are lower than the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ wells, whereas the light-hole exciton binding energy calculated by considering the effect of the exciton-LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for $x = 0.3$ is greater than the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well when the value of L_w is in the range of 4.0–7.0 nm. When we consider the effect of the exciton-LO phonon interaction for this range of L_w values, we expect the exciton characteristics to be predominant even at RT.

The strong interaction between the excitons and LO phonons usually results in the dissociation of the excitons at higher temperatures [9]. Ionization of excitons should be prevented in systems where the difference between the exciton binding energies of the 1s and 2s states is larger than the LO phonon energy [9]. For a more realistic understanding of the exciton stability, the calculation of the excited exciton states is necessary. This is not an easy task. To simplify our calculation, we discuss only the binding energy of the ground exciton state. Moreover, to simplify the calculations, we assume that the contribution of the off-diagonal terms in the exciton Hamiltonian as described by Luttinger–Kohn is extremely small because the degeneracy of the valence band of the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well at the Γ point is removed due to induced compressive strain in the $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ well. However, the contribution of the off-diagonal terms in the exciton Hamiltonian could not be completely ignored. Further research is necessary to obtain more accurate exciton states by theoretical calculation. Therefore, our result is not the whole story of the exciton stability.

We calculated the heavy- and light-hole exciton transition energies by considering the effect of the exciton-LO phonon energy in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs as functions of

FIG. 4: Heavy-hole (solid lines) and light-hole (broken lines) transition energies calculated by taking into account the effect of the exciton-LO phonon interaction energy in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs as functions of L_w for $x = 0.1, 0.2$, and 0.3 . Closed circles indicate the photoluminescence (PL) peak energies measured for $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs when $x = 0.3$ [25]; the open triangle, open square, and open circle indicate the PL peak energies measured for $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs at the L_w value of 8.1 nm for $x = 0.11, 0.22$, and 0.31 , respectively [26].

L_w for $x = 0.1, 0.2$, and 0.3 . Figure 4 shows the dependence of the heavy-hole (solid lines) and light-hole (broken lines) exciton transition energies on L_w . For comparison, the transition energies measured for $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs [25, 26] are also plotted. The transition energies of the heavy- and light-hole excitons decrease with increases in L_w because the electron, heavy-hole, and light-hole subband energies decrease with increases in L_w . The heavy-hole exciton transition energy is lower than the light-hole exciton transition energy because of the induced compressive strain. The changes in the transition energies of the heavy- and light-hole excitons with the L_w are essentially similar. The heavy-hole (light-hole) exciton transition energies measured experimentally are considerably lower than those calculated by us. The discrepancy between the theoretical and experimental data could be a result of a Stokes shift [3, 27] or a well width fluctuation [28, 29]. Further research is necessary for a fair comparison of the theoretical results with the experimental results.

IV. CONCLUSION

We study the effect of exciton-LO phonon interaction on the exciton binding energies in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs for values of x in the range 0.1–0.3. The heavy- and light-hole exciton binding energies increase with the exciton-LO phonon interaction. The maximum heavy-hole (light-hole) exciton binding energy calculated by taking into account the effect of LO phonon interaction at $x = 0.3$ is 56.2 meV (42.8 meV). The increase in the maximum heavy-hole (light-hole) exciton binding energy for $x = 0.3$

is 9.1 meV (4.9 meV). In narrow $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs, the heavy-hole exciton binding energy calculated by taking into account the exciton-LO phonon interaction for values of x in the range 0.1–0.3 exceed the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$. For narrow wells, the light-hole exciton binding energies calculated by taking into account

the effect of LO phonon interaction in $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs exceed the LO phonon energy of $\text{Cd}_x\text{Zn}_{1-x}\text{S}$ when $x = 0.3$. Therefore, $\text{Cd}_x\text{Zn}_{1-x}\text{S}/\text{ZnS}$ SQWs are potential candidates for UV applications on the basis of their exciton transitions.

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