Effect of Dielectric Mismatch on Exciton Binding Energy in 
ZnS/Mg0.2Zn0.8S Quantum Wells

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We calculate the binding energies of heavy- and light-hole excitons in ZnS/Mg0.2Zn0.8S single quantum wells (SQWs) as functions of the well width by using a variational method. We take into account the effect of the mismatch between the dielectric constants of the well and the barriers (dielectric mismatch effect) in our calculation. The increases in the heavy- and light-hole exciton binding energies in ZnS/Mg0.2Zn0.8S SQWs for a Mg content (x) of 1.0 are 58.9 meV and 60.2 meV, respectively. In the case of narrow wells, the heavy- and light-hole exciton binding energies calculated by considering the dielectric mismatch effect exceed the longitudinal optical phonon energy of ZnS when x \geq 0.3. [DOI: 10.1380/ejssnt.2010.145]

Keywords: Zinc sulfide; Band offset; Exciton binding energy; Dielectric mismatch

I. INTRODUCTION

The radiative recombination of excitons in ZnSe- and ZnO-based quantum wells (QWs) is expected to play an important role in the lasing process [1, 2]. In contrast to free-carriers transitions, exciton transitions are associated with a high oscillator strength and a sharp density of states. Thus, a lasing process based on excitonic recombination is expected to have a large gain and a low threshold. In particular, excitons in ZnO-based QWs can be useful for room temperature (RT) optical process since the exciton binding energy in bulk ZnO is 59 meV [3]. Ohtomo et al. reported the stimulated emission of excitons at RT in ZnO-based multiple QWs (MQWs) and measured the threshold to be less than 22 kW/cm$^2$ for well widths in the range 0.7-4.7 nm [4].

Monolithically integrated multilayer laser diodes (LDs) can be used to reduce the number of optical components in recordable optical media. However, the crystalline structure of AlGaAs (AlGaInP)-based semiconductors used in 780-nm (650-nm) LDs differs from that of ZnO-based semiconductors used in ultraviolet (UV) LDs. Since the crystalline structure of ZnS is the same as that of AlGaAs (AlGaInP), ZnS-based UV LDs can be employed in combination with AlGaAs (AlGaInP) LDs for the fabrication of monolithically integrated multilayer LDs.

Strong interactions between excitons and longitudinal optical (LO) phonons usually lead to the dissociation of the excitons at RT. Therefore, suppression of the exciton-LO phonon scattering is important. Dissociation of the excitons should be prevented in systems where the excitons have a higher energy than the LO phonons. In the case of ZnS, the bulk exciton binding energy (36 meV) is less 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 typically enhanced by a factor of 1.5-2 because of quantum confinement. Therefore, ZnS-based QWs have potential applications in the fabrication of UV LDs. In particular, ZnS/MgZnS QWs have been experimentally studied for their use in the fabrication of UV optoelectronic devices [5-7]. Changes in the exciton binding energies with the well width have been measured for ZnS/MgZnS QWs. [5, 6] The exciton binding energies in ZnS/MgZnS QWs calculated by considering and neglecting the Pollmann–Büttner (PB) potential have been reported [5, 8]. The difference between the measured and calculated exciton binding energies in ZnS/ZnMgS QWs has been determined by Senger and Bajaj [8]. However, the dependence of the exciton binding energy in ZnS/MgZnS QWs on barrier alloy content has not been investigated [5, 8]. With an increase in the Mg alloy content x, the total band gap discontinuity $\Delta E$ increases, and hence, the quantum confinement effect becomes stronger. Under these strong confinement conditions, ZnS/MgZnS QWs have a large exciton binding energy, and therefore, the exciton stability also increases. However, there is a large dielectric mismatch between ZnS and MgS [7, 9]. Kumagai and Takagahara (KT) [10] have indicated that in QWs, exciton binding energy calculated by considering the mismatch between the dielectric constants of the well and the barrier (dielectric mismatch effect) is larger than that calculated by neglecting this effect. Estimation of the exciton binding energies in ZnS/MgZnS QWs is necessary for tuning the optical properties of these QWs for various LD applications.

In this study, we calculate the heavy- and light-hole exciton binding energies as functions of the well width in ZnS/MgZnS QWs. Moreover, we calculate the increase in the exciton binding energy with $\Delta E$. We follow a variational approach and take into account the effect of dielectric mismatch between the well and the barrier layers. We determine the effect of this dielectric mismatch on the exciton binding energy by following the approach proposed by KT and compare the results of our calculations with the available experimental data. Moreover, we calculate the exciton transition energies for appropriate adjustment of the optical bandgap for various applications.

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II. CALCULATION METHODS

Greene et al. have reported a detailed method of calculating the exciton binding energy in QWs [11]. The exciton Hamiltonian [12] is given as

$$H = -\frac{\hbar^2}{2\mu_\pm} \left( \frac{\partial^2}{\partial r^2} + \frac{\partial^2}{\partial z_\pm^2} \right) - \frac{\epsilon_0^2}{\epsilon \sqrt{r^2 + (z_\pm - z_h)^2}} + V_c(z_e) + V_h(z_h) + V_{KT},$$

(1)

where $\mu_\pm$ is the reduced effective mass of the exciton, and $\epsilon$ is the dielectric constant. $V_c(z_e)$ and $V_h(z_h)$ are the conduction and valence band offsets, respectively, and $V_{KT}$ is the correction term derived by considering the image charge effect, as defined by KT [10]. Since the above-mentioned expression is given in the form of an infinite series, it becomes very lengthy. For example, when the electron and holes are in the well, $V_{KT}$ is given as [13]

$$V_{KT} = -\sum_{n=-\infty}^{\infty} \xi_n \phi_s \frac{\epsilon_0^2}{\epsilon^2 \sqrt{r^2 + (z_e - z_h - nL_w)^2}},$$

(2)

where $\xi = (\epsilon_0^2 - \epsilon_\pm^2)/(\epsilon_0^2 + \epsilon_\pm^2)$, and $\epsilon_\pm$ are the static dielectric constants for the well and the barrier, respectively. $L_w$ is the well width. Details of the method of calculating the exciton binding energies by considering the effect of dielectric mismatch on the electron–hole Coulomb interaction are provided in Ref. [10].

A trial function [12] is given as

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

(3)

where $\phi_e(z_e)$ and $\phi_h(z_h)$ are the electron and heavy-hole wave functions, respectively, and $\alpha$ and $\beta$ are variational parameters. The effective masses of the electron, heavy-hole, and light-hole are assumed to be position independent for simplification of our calculation; further, these effective masses are equal to those in ZnS.

Here, we assume that the barrier width in Mg$_x$Zn$_{1-x}$S is considerably larger than the critical thickness of the barrier layer; therefore, the lattice constant of the Mg$_x$Zn$_{1-x}$S barrier approaches the bulk value. We also assume that the lattice constant of ZnS conforms to that of Mg$_x$Zn$_{1-x}$S when the ZnS well is sandwiched between two Mg$_x$Zn$_{1-x}$S barriers. Under these conditions, we calculate the critical thickness of the ZnS well in Mg$_x$Zn$_{1-x}$S by using Matthews and Blakeslee’s (MB’s) mechanical equilibrium model [14]. The critical thickness $h_c$ is given by

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

(4)

where $\nu$ is Poisson’s ratio; $f$, the lattice mismatch between ZnS and Mg$_x$Zn$_{1-x}$S; and $b$, the Burgers vector. Here, we assume that $b = \sqrt{2a}$, $1 = \alpha = 0$, and $\cos \lambda = 1$; $a$ is the lattice constant of the ZnS well.

Band offsets have been calculated by using the “model-solid approach.” [15] The heavy-hole band offset $V_{hh}$ (light-hole band offset is $V_{lh}$) is calculated as the difference between the energies at the top of the heavy-hole (light-hole) bands in ZnS and Mg$_x$Zn$_{1-x}$S, and the conduction band offset $V_c$ is calculated as the difference between the energies at the bottom of the conduction bands in ZnS and Mg$_x$Zn$_{1-x}$S.

The energy at the top of the heavy-hole (light-hole) band in strained ZnS is defined as the summation of the energy at the top of the valence band in unstrained ZnS and the energy shift of the heavy-hole (light-hole) band in strained ZnS, whereas, the energy at the bottom of the conduction band in strained ZnS is defined as the summation of the energy at the bottom of the conduction band in unstrained ZnS and the energy shift of the conduction band in strained ZnS.

The energy at the top of the valence band in unstrained Mg$_x$Zn$_{1-x}$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 Mg$_x$Zn$_{1-x}$S is calculated by linear interpolation using a bowing parameter.

The following relations are used to describe the energy shifts of the conduction ($dE_c$), heavy-hole ($dE_{hh}$), and light-hole ($dE_{lh}$) bands with strain [5]:

$$\varepsilon = \frac{a_h - a_w}{a_w},$$

(5)

$$\varepsilon_{zz} = \frac{-2C_{12}}{C_{11}} \varepsilon,$$

(6)

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

(7)

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

(8)

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

(9)

$$dE_{hh} = E_H + E_S,$$

(10)

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

(11)

where $a_w$ and $a_h$ are the lattice constants of the ZnS wells and Mg$_x$Zn$_{1-x}$S barriers, respectively. $\varepsilon_{ij}$ is the strain tensor, and $C_{ij}$ is the elastic stiffness constant.

Electron, heavy-hole, and light-hole subband energies are determined by numerically solving the equation for a finite square-well potential [11].

The heavy-hole (light-hole) exciton transition energy is obtained by subtracting the heavy-hole (light-hole) exciton binding energy from the effective heavy-hole (light-hole) bandgap energy. The effective heavy-hole (light-hole) bandgap energy is given by the summation of the minimum conduction subband energy, minimum heavy-hole (light-hole) subband energy, and heavy-hole (light-hole) bandgap energy of the well layer.
TABLE I: Physical parameters used in the calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ZnS</th>
<th>MgS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice constant, a (nm)</td>
<td>0.54093 [16]</td>
<td>0.562 [17]</td>
</tr>
<tr>
<td>Bandgap energy at 4.2 K, $E_g$ (eV)</td>
<td>3.84 [16]</td>
<td>4.8 [17]</td>
</tr>
<tr>
<td>Energy at the top of the valence band, $E_{cv}$ (eV)</td>
<td>-11.84 [18]</td>
<td>-11.93 [19]</td>
</tr>
<tr>
<td>Deformation potential, $a_e$ (eV)</td>
<td>-2.78 [16]</td>
<td>1.2 [16]</td>
</tr>
<tr>
<td>$b$ (eV)</td>
<td>-0.7 [16]</td>
<td>0.75 [20]</td>
</tr>
<tr>
<td>Spin-orbit splitting energy, $\Delta_{so}$ (eV)</td>
<td>0.072 [16]</td>
<td>0.28 [20]</td>
</tr>
<tr>
<td>Effective mass of the electron, $m_e$ ($m_0$)</td>
<td>2.54 [20]</td>
<td>0.75 [20]</td>
</tr>
<tr>
<td>Luttinger parameter, $\gamma_1$</td>
<td>8.9 [8]</td>
<td>4.506 [9]</td>
</tr>
<tr>
<td>Luttinger parameter, $\gamma_2$</td>
<td>0.96 [20]</td>
<td>3.453 [11]</td>
</tr>
<tr>
<td>Relative dielectric constant, $\epsilon$ ($\epsilon_0$)</td>
<td>2.54 [20]</td>
<td>0.75 [20]</td>
</tr>
</tbody>
</table>

The physical parameters used for our calculation are listed in Table I. Here, $C_{ZnMgS} = 0.0698$ eV [21]. Lawaetz’s parameter set is used to evaluate the anisotropic effective masses of the heavy- and light-holes [20]. The effective masses of the heavy- and light-holes in the $x$-direction are calculated to be $m_+ = 1/(\gamma_1 - 2\gamma_2) = 0.96m_0$ and $m_- = 1/(\gamma_1 + 2\gamma_2) = 0.44m_0$, respectively. The effective masses of heavy- and light-holes calculated for the $x$-$y$ plane are $m_{+/+} = 1/(\gamma_1 + \gamma_2) = 0.30m_0$ and $m_{+/--} = 1/(\gamma_1 - \gamma_2) = 0.56m_0$, respectively. The parameters pertaining to the alloy material are derived by linear interpolation.

We calculate the critical thickness $h_c$ of the ZnS well in Mg$_x$Zn$_{1-x}$S when $x$ is in the range 0.1–1.0. Figure 1 shows the calculated results. It is apparent that $h_c$ decreases with an increase in $x$. The $h_c$ values corresponding to $x = 0.1$ and $x = 1.0$ differ by one order of magnitude. When calculating the exciton binding energy for $x \geq 0.4$, the thickness of ZnS wells is assumed to be close to the critical thickness. For calculating the heavy- and light-hole exciton binding energies, the thicknesses of the ZnS wells for $x = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0$ are taken as $20$ nm, $20$ nm, $20$ nm, $15$ nm, $10$ nm, $8$ nm, $6$ nm, $5$ nm, $4$ nm, and $4$ nm, respectively.

We calculate $V_c$, $V_{hh}$, and $V_{lh}$ as functions of $x$ in ZnS/Mg$_x$Zn$_{1-x}$S SQWs for up to $x$ values 1.0. Figure 2 shows the calculated results. $V_c$, $V_{hh}$, and $V_{lh}$ increase with $x$ because $\Delta E$ increases with $x$. $V_{lh}$ is greater than $V_{hh}$ because of the induced tensile strain. In this system, the lattice constant of the Mg$_x$Zn$_{1-x}$S barriers is greater than that of the ZnS wells. As a result, tensile strain is induced in the ZnS wells.

Figure 3 shows the heavy- and light-hole exciton binding energies calculated by considering and neglecting the dielectric mismatch effect in ZnS/Mg$_x$Zn$_{1-x}$S SQWs for $x = 0.2$. The exciton binding energies are calculated as functions of the well width. For comparison, the heavy- and light-hole exciton binding energies measured for ZnS/Mg$_x$Zn$_{1-x}$S SQWs when $x = 0.19$ [6] are also
EXCITON BINDING ENERGIES FOR WIDE WELLS

The exciton binding energies for wide wells agree with those calculated by considering the dielectric mismatch effect in ZnS/Mg$_x$Zn$_{1-x}$S SQWs as functions of well width for $x = 0.2$. Solid and dashed (dashed and dashed-dotted) curves indicate the heavy- and light-hole exciton binding energies obtained by neglecting (considering) the dielectric mismatch effect, respectively. Closed circles and squares indicate the experimental data reported by Urbaszek et al. for ZnS/Mg$_x$Zn$_{1-x}$S SQWs at $x = 0.19$. [6]

FIG. 3: Heavy-hole and light-hole exciton binding energies calculated by neglecting and considering the dielectric mismatch effect in ZnS/Mg$_x$Zn$_{1-x}$S SQWs as functions of well width for $x = 0.2$. Solid and dashed (dashed and dashed-dotted) curves indicate the heavy- and light-hole exciton binding energies obtained by neglecting (considering) the dielectric mismatch effect, respectively. Closed circles and squares indicate the experimental data reported by Urbaszek et al. for ZnS/Mg$_x$Zn$_{1-x}$S SQWs at $x = 0.19$. [6]

The changes in the binding energies of the heavy- and light-hole excitons with the well width are essentially similar. Even after considering the dielectric mismatch effect, the changes in the binding energies of the heavy- and light-hole excitons are not significant. The maximum heavy-hole (light-hole) exciton binding energy calculated by considering the dielectric mismatch effect is 42.9 meV (44.6 meV), whereas the maximum heavy-hole (light-hole) exciton binding energy calculated by neglecting the dielectric mismatch effect is 38.9 meV (40.9 meV). The increase in the maximum heavy-hole (light-hole) exciton binding energy in ZnS/Mg$_x$Zn$_{1-x}$S SQWs for $x = 0.2$ is calculated to be 3.9 meV (3.7 meV) by considering the dielectric mismatch effect.

The maximum heavy- and light-hole exciton binding energies calculated by considering the dielectric mismatch effect are smaller than those measured by Urbaszek et al. for ZnS/Mg$_x$Zn$_{1-x}$S SQWs at $x = 0.19$ [6]. The heavy-hole (light-hole) exciton binding energy measured for a well width of 4 nm (3.5 nm) is considerably larger than that calculated by considering the dielectric mismatch effect. The measured heavy- and light-hole exciton binding energies show a marked decrease when the well width increases from 3 nm to 5 nm. The reason for this anomalous behavior is unknown. The values of the heavy-hole (light-hole) exciton binding energies for wide wells agree with those calculated by considering the dielectric mismatch effect. However, the light-hole exciton binding energy measured for a well width of 10 nm is lesser than that calculated by ignoring the dielectric mismatch effect. For fair comparison of the theoretical results with the experimental results, further research is necessary.

We have calculated the heavy- and light-hole exciton binding energies in ZnS/Mg$_x$Zn$_{1-x}$S SQWs as functions of the well width by neglecting and considering the dielectric mismatch effect for $x = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,$ and $1.0$. Figures 4(a) and 4(b) show the heavy-hole exciton binding energies calculated by neglecting and considering the dielectric mismatch effect, respectively. Figures 5(a) and 5(b) show the light-hole exciton binding energies calculated by neglecting and considering the dielectric mismatch effect, respectively.

With a decrease in the well width, the heavy- and light-hole exciton binding energies increase to a maximum and then decrease rapidly. This is because when the well width decreases, the exciton wave function is compressed in the wells and extends to the barrier region. [11] The shape of the curve obtained for the dependence of the heavy- and light-hole exciton binding energies on the well width is consistent with that reported by Greene et al. [11] Changes in the binding energies of the heavy- and light-hole excitons with the well width are essentially similar.

The heavy-hole (light-hole) exciton binding energy calculated by considering the image effect charge increases with $x$, reaching a value of 111.9 meV (119.4 meV) at $x = 1.0$. When $x \geq 0.3$, the heavy- and light-hole exciton binding energies calculated for narrow wells by considering the dielectric mismatch effect are larger than the LO phonon energy of ZnS (44 meV). Thus, the exciton characteristics are predominant even at RT. The strong interaction between the excitons and LO phonons usually results in the dissociation of the excitons at higher temperatures [5, 6]. Ionization of excitons should be prevented in...
energies in ZnS/Mg$_{1-x}$S SQWs as functions of well width for $x = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,$ and 1.0. Open squares indicate the transition energies of the heavy- and light-hole excitons measured for ZnS/Mg$_{1-x}$S SQWs when $x = 0.19$ [6], whereas open circles indicate the transition energies of the heavy- and light-hole excitons measured for ZnS/Mg$_{1-x}$S SQWs when $x = 0.21$ [7].

We calculated the heavy- and light-hole exciton transition energies in ZnS/Mg$_{1-x}$S SQWs as functions of well width by considering the dielectric mismatch effect for $x = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,$ and 1.0. Figures 6(a) and 6(b) show the calculated heavy- and light-hole exciton transition energies for wide wells decrease with $x$ because the heavy- and light-hole exciton transition energies for wide wells decrease with $x$ because the heavy- and light-hole bandgap decreases with $x$. This bandgap decrease in turn is due to the induced tensile strain. Figure 7 shows the dependence of the excitonic transition energies for well widths of 1 nm and 4 nm on $x$, respectively. The heavy- and light-hole exciton transition energies for narrow wells increase with $x$ because $\Delta E$ increases with $x$. On the other hand, the heavy- and light-hole exciton transition energies for wide wells decrease with $x$ because the heavy- and light-hole bandgap energies decrease with $x$: this bandgap energy decrease in turn is due to the induced tensile strain. For wide wells, the energy separation between the heavy- and light-hole exciton transitions increases with $x$. For example, Figure 7 shows the energy separation between the heavy- and light-hole exciton transitions at a well width of 10 nm. The maximum energy separation between the heavy- and light-hole exciton transitions increases with $x$ and reaches 155.4 meV at $x = 1.0$.

Owing to induced tensile strain in the ZnS well, the de-
binding energies of the heavy- and light-hole excitons is an easy task. For simplification of our calculation, the both the heavy-hole and light-hole states [26]. This is not we need to solve for the exciton Hamiltonian including termine the accurate exciton states under this condition, of the heavy- and light-hole excitons. In order to de-
exciton transitions is comparable to the binding energies
the energy separation between the heavy- and light-hole

generacy of the valence band of the ZnS well at the Γ point
is removed. This leads to the formation of two indepen-
dent exciton systems, the heavy-hole exciton and light-
hole exciton. When the value of
is in the range 0.2-0.4,
the energy separation between the heavy- and light-hole
exciton transitions is comparable to the binding energies of
the heavy- and light-hole excitons. In order to de-
terminate the accurate exciton states under this condition,
we need to solve for the exciton Hamiltonian including
both the heavy-hole and light-hole states [26]. This is not
an easy task. For simplification of our calculation, the
binding energies of the heavy- and light-hole excitons are
calculated separately.

IV. CONCLUSION

We calculated the binding energies of heavy- and light-
hole excitons in ZnS/Mg$_x$Zn$_{1-x}$S SQWs by considering the
dielectric mismatch effect. The heavy-hole (light-hole) exciton binding energy calculated by considering this
effect increases with $x$ and reaches 111.9 meV (119.4 meV) at $x = 1.0$. The increase in the maximum binding energy
of the heavy-hole (light-hole) exciton for $x = 1.0$ is 58.9 meV (60.2 meV). The dependence of the light-hole exciton binding energy on well width is qualitatively the same as that observed for the heavy-hole exciton binding energy.

We also calculated the transition energies of heavy-
and light-hole excitons in ZnS/Mg$_x$Zn$_{1-x}$S SQWs by considering the dielectric mismatch effect. For wide wells, the light-hole exciton transition energy is lower than the heavy-hole exciton transition energy because of the induced tensile strain in the ZnS wells. The heavy- and light-hole exciton transition energies for narrow wells increase with $x$. For wide wells, the heavy- and light-hole exciton transition energies decrease with $x$ because the heavy- and light-hole bandgap energies decrease with $x$ when the well width exceeds 1 nm. As $x$ increases, the energy separation between the heavy- and light-hole exciton transitions at a well width of 10 nm increases, reaching a value of 155.4 meV for $x = 1.0$.

For narrow wells, the heavy- and light-hole exciton binding energies in ZnS/Mg$_x$Zn$_{1-x}$S SQWs exceed the LO phonon energy of ZnS when $x \geq 0.3$. Therefore, ZnS/Mg$_x$Zn$_{1-x}$S SQWs are potential candidates for UV applications based on exciton transitions.

<table>
<thead>
<tr>
<th>$x$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-hole $L_w$ for heavy-hole</td>
<td>1.5</td>
<td>3.9</td>
<td>7.0</td>
<td>11.4</td>
<td>16.1</td>
<td>21.8</td>
<td>28.6</td>
<td>36.9</td>
<td>46.8</td>
<td>58.9</td>
</tr>
<tr>
<td>Light-hole $L_w$ for light-hole</td>
<td>5.0</td>
<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

Table II: Increase in maximum heavy- and light-hole exciton binding energies (meV) and the well width ($L_w$) for the maximum heavy-hole (light-hole) exciton binding energy (nm).

\[ L_w = 1 \text{ nm} \]
\[ L_w = 4 \text{ nm} \]

FIG. 7: Calculated heavy-hole (closed circles) and light-hole (closed squares) exciton transition energies for well widths ($L_w$) of 1 nm and 4 nm and energy separation between heavy-
and light-hole exciton transitions (open circles) at a $L_w = 10$

nm in ZnS/Mg$_x$Zn$_{1-x}$S SQWs as functions of $x$. Calculations
have been made by considering the dielectric mismatch effect. The solid lines are a guide to the eye.

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