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# Electric-field control of electron–hole wave functions in a wide quantum well

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**Abstract**

The electric field dependence of the electron/hole wave function and the radiation energy of an exciton in a Be-δ-doped 80 nm quantum well (QW) is studied experimentally and compared it with variational calculation. The photoluminescence (PL) spectra show Stark shifts depending on the gate electric field and PL intensity of the exciton of the first excited state has a dip in the electric-field dependence which reflects the node of the electron wave function.


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*Keywords:* Quantum confined Stark effect; Photoluminescence; Quantum well; Exciton

## 1. Introduction

The double-gated quantum well (QW) exhibits high controllability of the confinement potential profile in the QW with the gate voltages [1–3]. The potential shape of the QW depends on the voltage difference $V = V_b - V_f$, where $V_b$ and $V_f$ are the back- and front-gate voltages, respectively. The electrostatic potential is tilted towards the front side or the back side depending on $V$. The photo-excited electrons and holes are spatially separated to either side of the QW in a strong electric field. If the overlap of the wave functions can be controlled with $V$ in a weak electric field, it is possible to observe the properties of the shape of the wave function such as nodes of the excited state in the amplitude of the optical absorption (OA) or of the photoluminescence (PL) when $V$ is swept. However, because of the attraction by the Coulomb interaction between the electron and the hole, the overlap of the wave functions is not simply argued by the individual single-particle picture. It is important to take the Coulomb interaction into account to discuss in the electric-field dependence of OA or PL.

In this paper, we report on the model and PL measurement of the Be-δ-doped 80 nm GaAs QW. In Section 2, we assume the potential of the δ-doped acceptor (Be) to be a triangular shape in the QW as shown in Fig. 1 and calculated the electron and hole wave functions with a variational calculation. The PL measurement with changing the gate voltage difference is presented in Section 3.

## 2. Variational calculation of exciton binding energy and wave function

To take the Coulomb interaction between the electron and the hole into account, we consider the exciton Hamiltonian of 1*s*-type as

$$H = H_{ez} + H_{hz} + H_{e-h}, \quad (1)$$

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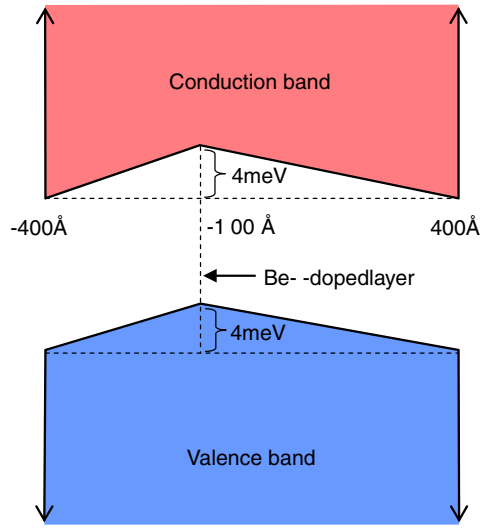


Fig. 1. The model of the band structure of Be-δ-doped 80 nm QW. The Be atoms are δ doped at 10 nm from the center. The left (right) hand side is corresponding to the back (front) side.

$$H_{\mathrm{e(h)}z} = -\frac{\hbar^2}{2m_{\mathrm{e(h)}}}\frac{\partial^2}{\partial z_{\mathrm{e(h)}}^2} + V(z_{\mathrm{e(h)}}) \mp eEz_{\mathrm{e(h)}}, \tag{2}$$

$$H_{\mathrm{e-h}} = -\frac{\hbar^2}{2\mu}\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r} - \frac{e^2}{4\pi\varepsilon}\frac{1}{\sqrt{(z_{\mathrm{e}} - z_{\mathrm{h}})^2 + r^2}}, \tag{3}$$

where $m_{\mathrm{e(h)}}$ and $-e(e)$ are the effective mass with the $z$ coordinate and the charge of an electron (hole), $E$ is an electric field in the $z$ direction, $\mu^{-1} = m_{\mathrm{e}}^{-1} + m_{\mathrm{h}}^{-1}$ is the reduced mass of the exciton for the relative motion in the $x$–$y$ plane, and $V(z_{\mathrm{e(h)}})$ is the potential profile, which is illustrated in Fig. 1. We assume a trial function for an exciton [4] as

$$\Psi(\mathbf{r}, z_{\mathrm{e}}, z_{\mathrm{h}}) = \phi_{\mathrm{e}}(z_{\mathrm{e}})\phi_h(z_k)\varphi_{\mathrm{e-h}}(\mathbf{r}), \tag{4}$$

$$\phi_n^{\mathrm{e(h)}}(z) = \begin{cases} C_{\mathrm{e(h)}} \sin\left(\dfrac{\pi n_{\mathrm{e(h)}}}{L}\left(z + \dfrac{L}{2}\right)\right) e^{\beta_{\mathrm{e}}(h)z}, & |z| < L/2, \\ 0, & |z| \geqslant L/2, \end{cases} \tag{5}$$

$$\varphi_{\mathrm{e-h}}(\mathbf{r}) = \sqrt{\frac{2}{\pi}}\frac{1}{\lambda}\exp(-r/\lambda), \tag{6}$$

where $\phi_{\mathrm{e(h)}}(z_{\mathrm{e(h)}})$ is the wave function for an electron (hole) in the $z$ direction and $\varphi_{\mathrm{e-h}}(\mathbf{r})$ is the exciton wave function, and $\beta_{\mathrm{e}}$, $\beta_{\mathrm{h}}$, $\lambda$ are the variational parameters. By minimizing the total radiation energy of an exciton,

$$\langle H \rangle = \min_{\beta_{\mathrm{e}},\beta_{\mathrm{h}},\lambda} \langle \Psi \mid H \mid \Psi \rangle, \tag{7}$$

we obtain the exciton binding energy

$$E_{\mathrm{B}} = \langle \Psi \mid H_{\mathrm{e}z} + H_{\mathrm{h}z} \mid \Psi \rangle - \min_{\beta_{\mathrm{e}},\beta_{\mathrm{h}},\lambda} \langle \Psi \mid H \mid \Psi \rangle. \tag{8}$$

We consider the GaAs QW of the thickness 80 nm where the electron effective mass $m_{\mathrm{e}} = 0.065$, the heavy hole mass $m_{\mathrm{h}} = 0.45$, $\mu = 0.0415$ and $\varepsilon = 12.15$. For weak electric fields, the radiation energy decreases only slightly, whereas, for strong fields, the radiation energy decreases linearly due to the Stark shift. The upper panel of Fig. 2 shows the wave function distribution for the electron ground state ($n_{\mathrm{e}} = 1$) and the hole ground state ($n_{\mathrm{h}} = 1$). In Fig. 2, and the graphs hereafter, the axis of the electric field is translated to the gate bias voltage by $V = d \times E$, where $d = 800$ nm is the width between the front- and the back-gate of our sample. As the electric field is applied, the electron–hole pair is gradually separated towards the different sides of the QW. The hole wave function is more flexible to the electric field than the electron wave function because of the lighter effective hole mass. The lower panel of Fig. 2 shows the wave function distribution for the first excited state ($n_{\mathrm{e}} = 2$) electron and the ground state hole ($n_{\mathrm{h}} = 1$). In a weak field, the electron–hole pair is located on the left (back-gate) side of the well, because the hole favors to localize near the Be layer to gain the potential energy. For a strong electric field, the hole gradually moves towards the opposite side, passing over the node ($z = 0$) of the electron wave function and, in this case, dips appear in the overlap of the wave functions reflecting the node of the electron wave function as shown in Fig. 3. This behavior is quite in contrast to the Be-undoped case, where, in a weak field, the electron–hole pair is more stable when it is localized on the right (front-gate) side of the wall to gain the hole energy

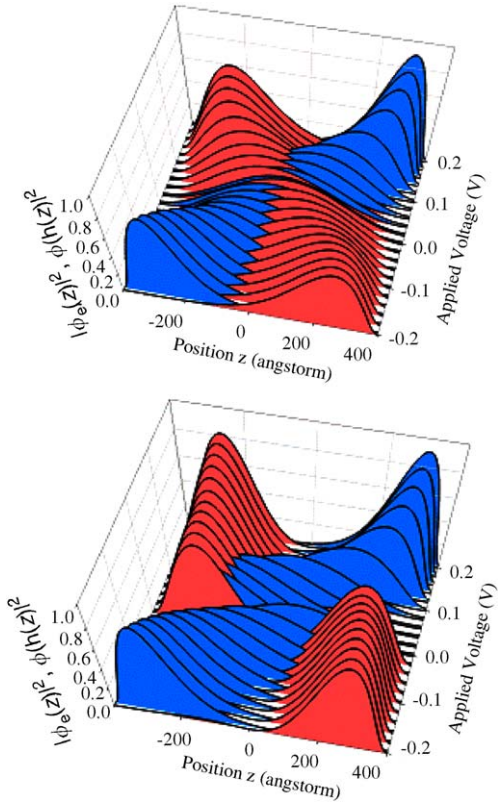


Fig. 2. Applied voltage dependence of the squared wave function of the ground-state/first excited-state electron (red curve) and heavy hole (blue curve) along the $z$ direction of the well (upper panel/lower panel).