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# THE ELECTRIC FIELD EFFECTS ON THE EXCITON BINDING ENERGIES OF THE COAXIAL CYLINDRICAL $(AlAs, Ga)/GaAs$ QUANTUM WELL WIRES

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**Abstract**
*The electronic properties of an exciton in a coaxial cylindrical quantum wire - formed by an central insulating AlAs cylinder surrounded with successive layers of GaAs, $Al_{x_1}Ga_{1-x_1}As$, GaAs, and $Al_{x_2}Ga_{1-x_2}As$ - were investigated. Exciton binding energies in such devices were calculated numerically using the effective mass approximation combined with the 4th-order Runge-Kutta method and with a variational approach were obtained for the two structure which are identified by differed well and barrier widths, Ground-state energies and probability densities for the electron, heavy and light holes were determined under a certain external electric field value, and the binding energy of heavy-hole and light-hole excitons were calculated. It was observed that the applied electric field caused significant effects on the exciton binding energies.*

**Keywords:** Exciton, quantum wire, electric field

## INTRODUCTION

Excitons as the bound pairs of an electron and a hole which are attracted to each other by the electrostatic Coulomb force are an indispensable concept in optoelectronics and quantum technologies. Having a clear understanding of exciton theory is essential in order to understand semiconductor behavior. It has been shown how the measurements of the excitonic linewidth at low temperatures using optical spectroscopic techniques such as photoluminescence, cathodoluminescence, and absorption can be used to provide information about the structural quality of quantum well structures [1].

As mentioned above, the physical properties of excitons in low-dimensional semiconductor systems have been investigated in recent years due to their high potential for application in electronic and optoelectronic devices [2,3]. The optical control of an exciton in quantum dots [4] and the investigation of the spectrum of excitonic quantum states in InAs/AlGaAs quantum dots [5] are examples of research on excitons. Excitonic properties exhibit significant changes under external electric and magnetic fields. For instance, the binding energies of excitons in quantum wires and interband optical absorption spectra have been investigated, and shown how the exciton binding energy varies depending on the wire dimensions and the applied electric field [6].

Geometric effects, as well as the effects of electric and magnetic fields, on impurity binding energies in multilayer quantum wires and quantum dots have previously been addressed in several studies [7-11]. More recently, excitons and the effects of magnetic fields in multilayer quantum wires have been investigated, demonstrating that the magnetic field influences the electronic properties of the excitons [12].

A cylindrical AlAs material is encapsulated


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in layers of GaAs, which are quantum well wires, and AlGaAs, which are the barriers between the wires, respectively. Exciton binding energies in this cylindrical quantum wire—composed of coaxial Al, As, and Ga alloy layers—have been investigated for various structural parameter values and electric field strengths.

## THEORY

Fig.1 shows schematically the coaxial cylindrical quantum well wire structure (CCQWWS) in which its excitonic properties are investigated.

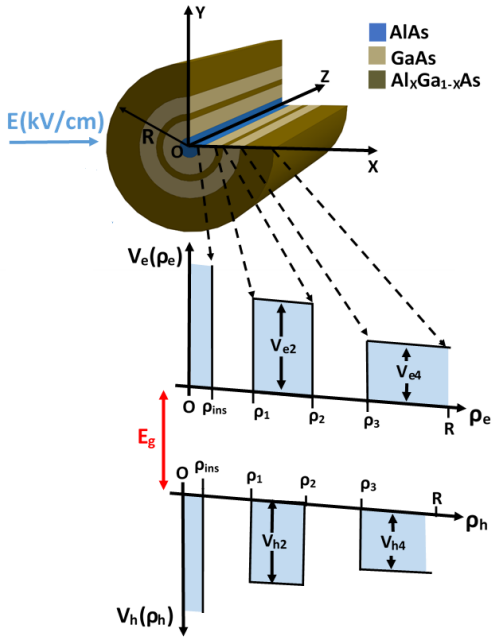



**Fig. 1**. *Schematic view of the CCQWWS and its potential profile sketch representing the electronic potential on the radii basis.*

In the effective mass approximation, the Hamiltonian of an exciton under an external electric field is

$$H = \frac{\vec{P}_e^2}{2m_e(\rho_e)} + V_e(\rho_e) + \eta\,\rho_e\cos\varphi + \frac{\vec{P}_h^2}{2m_h(\rho_h)} + V_h(\rho_h) - \eta\,\rho_h\cos\varphi - \frac{e^2}{\varepsilon|\vec{r}_e-\vec{r}_h|}\ , \quad (1)$$

where $\vec{P}_e$ and $\vec{P}_h$ are the momentum operators of electron and hole, respectively. In Eq.1, $m(\rho_{e(h)})$ is the electron (hole) effective mass which is used taking into account that it is differed in semiconductor structure they are in [13]. Also $\varepsilon$ is the static dielectric constant, and $\eta = |e|F$ while $F$ is the applied electric field strength, and $|\vec{r}_e - \vec{r}_h|$ is the spatial separation of the electron-hole pair which is given by $\sqrt{\rho_e^2 + \rho_h^2 - 2\rho_e\rho_h\cos(\varphi_e - \varphi_h) + (z_e - z_h)^2}$.

$V_{e(h)}(\rho_{e(h)})$ in Eq.1is the confining potential for an electron (hole) given by

$$V_{e(h)}(\rho_{e(h)}) = \begin{cases} \infty\,, & 0 \le \rho \le \rho_{ins} \\ 0\,, & \rho_{ins} < \rho < \rho_1 \\ V_{2e(h)}\,, & \rho_1 \le \rho \le \rho_2 \\ 0\,, & \rho_2 < \rho < \rho_3 \\ V_{4e(h)}\,, & \rho_3 \le \rho \le \infty \end{cases} . \quad (2)$$

The Schrödinger equations for the electron and holes (heavy or light) can be derived from the Hamiltonian in Eq.1 separately as

$$\left[\frac{\vec{P}_e^2}{2m_e(\rho_e)} + V_e(\rho_e) + \eta\rho_e\cos\varphi\right]\psi_{0e}(\rho_e) = E_{0e}\psi_{0e}(\rho_e) \quad , \quad (3a)$$

and

$$\left[\frac{\vec{P}_h^2}{2m_h(\rho_h)} + V_h(\rho_h) - \eta\rho_h\cos\varphi\right]\psi_{0h}(\rho_h) = E_{0h}\psi_{0h}(\rho_h) \quad . (3b)$$

In above equations, when there is an electric field applied perpendicular to axis of the wire and along the positive $x$ direction, the ground state wave function $\psi_{0e(h)}(\rho_{e(h)})$ and the subband energy $E_{0e(h)}$ are numerically calculated by using the fourth-order Runge-Kutta method [2]. The trial wave function is chosen as

$$\psi^F_{e(h)} = N_F\psi_{0e(h)}(\rho_{e(h)})e^{-\rho_{e(h)}\cos\varphi/\lambda_a}, \quad (4)$$

where $N_F$ is normalization constant, $\varphi$ is the angle in cylindrical coordinates. The $\lambda_a$ in Eq.(4) is the variational parameter which is determined by minimizing the expectation value $E_{e(h)}$ of the Schrödinger Eqs.3a and 3b.

The expectation value of the total exciton energy can then be calculated as

$$E = min_{\lambda} \frac{\langle \psi_{e-h}|H|\psi_{e-h}\rangle}{\langle \psi_{e-h}|\psi_{e-h}\rangle}. \qquad (5)$$

The expression for the excitonic trial wave function used in the variational solution is given by

$$\psi_{e-h} = N\psi_{F(e)}\psi_{F(h)}e^{-|\vec{r}_e-\vec{r}_h|/\lambda}, \qquad (6)$$

where $N$ is the normalization constant and $\lambda$ being the exciton radius is the variational parameter. Thus the exciton binding energy is obtained from

$$E_{e-h}^{bin} = E_e + E_h - E \ . \qquad (7)$$

## RESULTS and DISCUSSIONS

The well and barrier potential values in the layers of CCQWWS in Fig. 1 are given in Table 1 where the effective masses of the electrons, heavy holes and light holes as weighted by the free electron mass also presented [14]. The aluminum concentrations in both $Al_xGa_{1-x}As$ barriers were chosen equal to be $x = 0.3$. The band gap energies used are given in Table 1, as well.

**Table 1** *The local potential depths experienced by the electrons and holes, and the reduced masses of electrons, heavy holes and light holes in the layers of CCQWWS weighted by* $m_0 = 9.11x10^{-31}\ kg$ *free electron mass.*

| *Layer* | *AlAs* | *GaAs* | $Al_{0.3}Ga_{0.7}As$ |
|---|---|---|---|
| $V_e/meV$ | ∞ | 0 | 224 |
| $V_{hh}/meV$ | ∞ | 0 | 149 |
| $V_{lh}/meV$ | ∞ | 0 | 149 |
| $m_e^*/m_0$ | 0.180 | 0.067 | 0.098 |
| $m_{hh}/m_0$ | 0.500 | 0.340 | 0.0382 |
| $m_{lh}/m_0$ | 0.149 | 0.095 | 0.109 |

Let us parametrize the layer thicknesses of the CCQWWS in Fig. 1. The outer radius of the entire structure is denoted by $R$ and is taken to be 225 Å. The thickness of the outer $Al_{0.3}Ga_{0.7}As$ layer-$R_4 = R - \rho_3 = 35$ Å- is so chosen that the wave functions cannot leak to outside of the structure. $R_1 = \rho_1 - \rho_{ins}$ for the inner $GaAs$ layer, $R_2 = \rho_2 - \rho_1$ for the subsequent $Al_{0.3}Ga_{0.7}As$ layer which forms a potential barrier. The following $GaAs$ layer is defined as $R_3 = \rho_3 - \rho_2$.

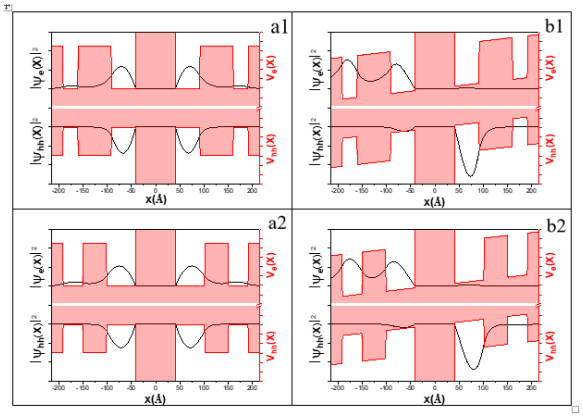



***Fig.2*** *The probability distribution of heavy hole exciton:* ***(a1)*** *in CCQWWS-1 without an electric field,* ***(a2)*** *as in Fig 2.a1, but for CCQWWS-2,* ***(b1)*** *in CCQWWS-1 with* $F = 30\ kV/cm$, *and* ***(b2)*** *as in Fig.2.b1, but for CCQWWS-2.*

We consider two geometrically different structures, namely CCQWWS-1 and CCQWWS-2. CCQWWS-1 has the structural parameters $R_1 = 50$ Å, $R_2 = 70$ Å and $R_3 = 30$ Å while the layer thicknesses of CCQWWS-2 are given as $R_1 = 60$ Å, $R_2 = 50$ Å and $R_3 = 40$ Å. Figs. 2.a1 and 2.a2 show the probability distribution of the exciton—formed by the binding of an electron and a heavy hole—within the structures of CCQWWS-1 and CCQWWS-2 in the absence of an external electric field. Although not clearly discernible from the figures, the change resulting from thinning the barrier between the two quantum wires manifests as a slight shift of the electron probability distribution toward the outer quantum wire, whereas no change is observed in the heavy-hole probability distribution. In Figs 2.b1 and 2.b2, when an external electric field is applied in the growth direction, the electron wave function in both structures becomes largely localized in the outer quantum wire, whereas the heavy-hole wave function becomes almost entirely localized in the inner quantum wire. Consequently, the field application increases the separation between the electron and the

heavy hole, and thus reduces the binding energy.

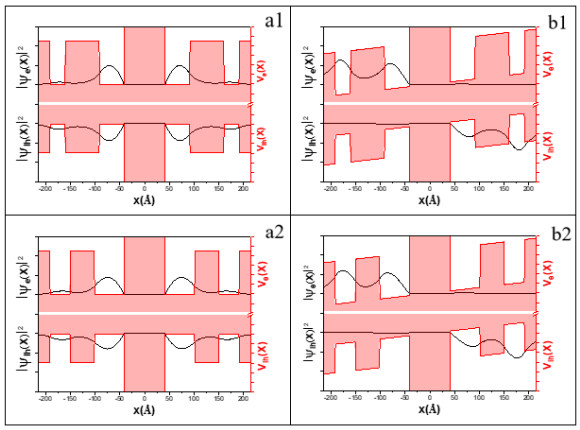



***Fig.3*** *The probability distribution of light hole exciton:* ***(a1)*** *in CCQWWS-1 without an electric field,* ***(a2)*** *as in Fig 3.a1, but for CCQWWS-2,* ***(b1)*** *in CCQWWS-1 with* $F = 30\ kV/cm$*, and* ***(b2)*** *as in Fig 3.b1, but for CCQWWS-2.*

Figs. 3. a1 and 3. a2 show the probability distribution of the light hole exciton in the structures of CCQWWS-1 and CCQWWS-2 without an external electric field. The variation resulting from thinning the barrier between the two quantum wires results in a slight shift of the electron probability distribution toward the outer quantum wire. The light hole probability distributions mimics that of the electron. When an external electric field is applied in the growth direction, the electron wave function in both structures becomes largely localized in the outer quantum wire, while the light-hole wave function also localizes similar to that of the electron as shown in Figs. 3. b1 and 3.b2. These distributions also result in a decrease in the binding energy.

The variation of heavy-hole and light-hole excitonic binding energies in CCQWWS-1 and CCQWWS-2 as a function of electric field strength is shown in Figs. 4a and 4b, respectively. As the electric field strength increases, the binding energy decreases exponentially for both structures and both excitons.

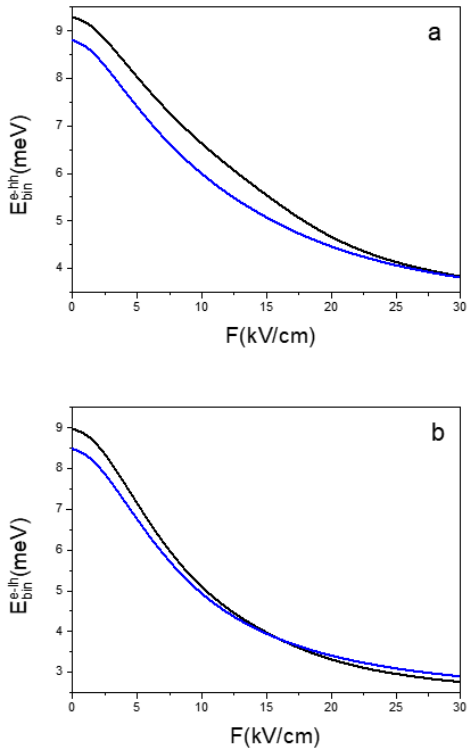



***Fig.4 (a)*** *The exciton binding energy of heavy hole exciton as function of electric field strength; the black curve is for the binding energy in CCQWWS-1, and the blue curve is for that in CCQWWS-2.* ***(b)*** *as in Fig.4a, but for the light hole exciton.*

## CONCLUSION

The probability distributions associated with heavy-hole/electron and light-hole/electron pairs exhibited interesting variations as the wire thicknesses increased. Also, the electric field strength increase causes exponential decrease in both the heavy-hole and the light-hole excitonic binding energies. The cross-over in the light-hole exciton binding energy between the two CCQWWSs observed for $\sim\mathbf{15}\ \boldsymbol{kV/cm}$ is to be studied.

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