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EXCITON-PHONON SYSTEM IN GaAs-Ga$_{1-x}$Al$_x$As QUANTUM-WELL WIRES

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ABSTRACT - The binding energies of light- and heavy- hole exciton-phonon systems in GaAs-Ga$_{1-x}$Al$_x$As quantum wires are calculated as a function of the sizes of the wire for several values of the heights of the barrier potential. It is found that the corrections due to exciton-phonon coupling are quite significant.

In the last few years some progress has been done in the study of electronic properties of quasi-one-dimensional semiconductor structures [1,4]. In these systems the electron motion is quantized in two directions (y and z) perpendicular to the wire and is free along the length of the wire (x). Sakaki [1] investigated the electron transport of ultra-thin GaAs-Ga$_{1-x}$Al$_x$As quantum wires and showed that a high-mobility effect would be expected. After Petroff, Gossard, Logan and Wiegmann [2] fabricated and observed cathodoluminescence which was attributed to transitions involving exciton states. More recently several authors have reported calculations of the mobility of electrons scattered by ionized donors and also by optical and acoustic phonons. The binding energies of hydrogenic impurity placed in a quantum-well wire of GaAs have been calculated and the results are larger than those in comparable two-dimensional quantum wells [3]. One of the important features of these one-dimensional semiconductor structure is the presence of excitons which play a fundamental role in the cathodoluminescence spectra of these systems. Because of the energy-band discontinuity at the interface between the two semiconductors the degeneracy of the valence band of GaAs is removed enough that these may be treated as isolated bands, leading as a consequence to two-exciton systems, namely, a heavy-hole exciton and a light-hole exciton.

This paper reports the calculation of exciton binding energies in a quantum-well wire of GaAs surrounded by Ga$_{1-x}$Al$_x$As with square cross section and finite height barrier for the confining potential. We have also calculated the effects of electron- and hole- optical phonon interaction on the exciton binding energies and showed that the corrections are quite significant. We find that both the magnitude and the behavior of the polaronic contribution are completely different from those recently calculated using infinite barrier potential [4].
In the framework of the effective-mass approximation the Hamiltonian of this system can be written as:

\[
H = E_g + \frac{p_{ye}^2 + p_{ze}^2}{2m_e} + \frac{p_{yh}^2}{2m_{yh}} + \frac{p_{zh}^2}{2m_{zh}} + \frac{p_{X}^2}{2M_T} + \frac{p_{X}^2}{2}\nonumber
\]

\[
- \epsilon(x^2 + (y_e - y_h)^2 + (z_e - z_h)^2) + V(y,z) + \sum_q \hbar \omega \ a_q^+ a_q^\dagger
\]

\[
+ \sum_q [\Gamma_q e^{iQ \cdot \hat{X}} e^{iQ \cdot \hat{R}_e} e^{iQ \cdot \hat{R}_h} e^{-iQ \cdot \hat{Q}_e} e^{-iQ \cdot \hat{Q}_h} a_q^+ + h.c.] , \tag{1}
\]

where \( E_g \) is the GaAs band gap, \( m_e, m_{yh}, m_{zh} \) are the band masses of the electron and the hole in the \( y(z) \) direction respectively, \( \hat{R}_i = (y_i, z_i) \) and \( \hat{P}_i = (p_{yi}, p_{zi}) \), \( i = e, h \) are the in-plane projection of the electron and hole coordinates and momenta; \( X, P_X \) are the center-of-mass coordinate and momentum, \( x, P_X \) are the electron-hole relative position and momentum, \( M_T = m_{xh} + m_e \) is the total mass along the \( x \) direction, \( \mu = m_{xh} m_e / M_T \) is the reduced mass for the \( x \) motion, \( \beta_e = m_e / M_T \) and \( \beta_h = m_{xh} / M_T \). \( \Gamma_q \) is the Fourier coefficient of the electron- and hole-phonon interaction [4] and \( V(y,z) \) is the confined potential well for the electron and hole, \( V(y,z) = 0 \) for \( |y| < L/2 \) and \( |z| < L/2 \), \( V(y,z) = V_{oy} \) for \( |y| > L/2 \) and \( V(y,z) = V_{oz} \) for \( |z| > L/2 \). \( a_q^+ \) is the creation operator for the optical phonons of wave vector \( \hat{q} = (q_x, q_z) \) and frequency \( \omega_0 \).

The binding energy of the exciton will be obtained by choosing a product ansatz for the trial wave function:

\[
\psi(\hat{r}_e, \hat{r}_h) = \sqrt{\lambda/2} \Phi_e(y_e) \zeta_e(z_e) \Phi_h(y_h) \zeta_h(z_h) e^{-\lambda |x|/2} \psi(0) \tag{2}
\]

where \( \Phi(y) \) and \( \zeta(z) \) are the exact ground-state wave functions for finite square-well potentials, \( \lambda \) is a variational parameter, \( U \) is a unitary transformation which displaces the phonon coordinates and \( |0\rangle \) represents the vacuum state. The expectation value of the Hamiltonian \( E = \langle \psi | H | \psi \rangle \), has then the following variational form:

\[
E = E_g + E_{kin} + E_{coul} + E_{pol} \tag{3}
\]

where \( E_{kin} \) is the kinetic energy, \( E_{coul} \) is the coulombic energy and \( E_{pol} \) is the polaronic contribution which can be easily obtained in a standard way [5]. We then obtain for the coulombic energy:

\[
E_{coul} = -2\lambda^2 e^2 \int dQ \frac{F_{eh}(Q)}{\lambda^2 + Q^2} \tag{4}
\]

and for the polaronic energy,
where the form factor associated with the quasi-one-dimensional confinement of electrons and holes is given by

\[ F_{\text{pol}} = -\frac{e^2 \hbar \omega}{\pi} \left( \frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0} \right) \int \frac{dQ}{\hbar^2 \omega + \hbar^2 Q^2 / 2M_T} \left\{ \frac{F_{\text{ee}}(Q)}{1 + (\beta_e Q/\lambda)^2} + \frac{F_{\text{hh}}(Q)}{[1 + (\beta_h Q/\lambda)^2]^2} - \frac{2F_{\text{eh}}(Q)}{(1 + (\beta_e Q/\lambda)^2)(1 + (\beta_h Q/\lambda)^2)} \right\} , \tag{5} \]

where \( \omega \) is the frequency, \( \hbar \) is the reduced Planck constant, \( \varepsilon_\infty \) and \( \varepsilon_0 \) are the high- and low-frequency dielectric constants, \( M_T \) is the effective mass, \( \beta_e \) and \( \beta_h \) are the effective mass ratios for electrons and holes, respectively, and \( \lambda \) is the wavelength of light.

We have numerically minimized the energy expression given by Eq. 3 with respect to the variational parameter \( \lambda \), with and without the presence of the electron- and hole-phonon interactions as a function of the size of the quantum wire for several values of the height of the potential barrier. In the present calculations we have used the following physical parameters: \( \varepsilon_\infty = 10.9, \varepsilon_0 = 12.5, \hbar \omega = 36.77 \text{ meV}, m_e = 0.0665 m_\text{o}, m_y = 0.0665 m_\text{o}, \)

\[ m_{\text{yyh}} = (\gamma_1 + \gamma_2)^{-1} m_\text{o}, \quad m_{\text{yyh}} = (\gamma_1 - \gamma_2)^{-1} m_\text{o}, \]

\[ m_{\text{zhh}} = (\gamma_1 - 2\gamma_2)^{-1} m_\text{o}, \quad m_{\text{zhh}} = (\gamma_1 + 2\gamma_2)^{-1} m_\text{o}, \]

where \( \gamma_1 = 6.85 \) and \( \gamma_2 = 2.1 \) for GaAs; \( \gamma_1 = 6.85 - 3.4 x \) and \( \gamma_2 = 2.1 - 1.42 x \) for \( \text{Ga}_{1-x}\text{Al}_x\text{As}. \)

The masses in the \( x \)-direction are the same as in the \( y \)-direction. The values of the potential barrier for electrons and holes are taken to be 60% and 40% of the energy-band-gap discontinuity \( \Delta E_g = 1.04 x + 0.47 x^2 \).

The results we have obtained for the exciton binding energies with and without the presence of phonons are shown in the figures as a function of the size of the wire and for several values of the potential barrier height. There are several interesting features to be noted from the results of our calculations. Firstly, one notices that the values of the exciton binding energies are about twice larger than those in comparable two-dimensional quantum wells [6]. These results are consistent with the observed cathodoluminescence in quantum wires by Petroff et al., whose observed the value of the exciton binding energy at 8–10 meV higher than that in two-dimensional quantum wells. We may note from the figures that for a given concentration \( x \) the values of the exciton binding energies have the same qualitative behavior as those previously obtained for the two-dimensional quantum wells, i.e., the exciton binding energies increase with increasing the size of the wire, reach a maximum value and finally decrease monotonically for larger wires. We also can observe that for a given \( x \) the light-hole exciton binding energy is systematically higher value than the heavy-hole exciton energy. As it can be seen, by interchanging the values of the potential barrier heights in the two directions perpendicular to the wire (which are represented in the figures by a pair of values of Al concentration) we obtain different values for the exciton binding energies; the masses of the holes are not the same in the two directions perpendicular to the wire. Finally, the figures also show that the electron- and hole-optical phonons interaction effects are extremely important, mainly in the limit of thin wire of GaAs.
In conclusion, we have presented the results for the exciton binding energies with and without the presence of phonons as a function of the size of the GaAs quantum wire and for several values of the heights of the potential barriers. We have shown that the polaronic contribution is extremely important and can not be neglected.

Heavy-hole and light-hole exciton binding energies as a function of the size of the quantum wire for different values of the height of the potential barriers. The numbers in the parenthesis indicate the Al concentration in the directions y and z respectively. The solid and dashed curves correspond to the case with and without the electron- and hole-phonon interactions.

REFERENCES