Effects of Periodic Gate Potentials on Quasi-1D Excitons

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Optical properties of Quasi-1D excitons in a GaAs-AlGaAs quantum well and confined by lateral field effect induced superlattice potentials are investigated. A variational approach is used to calculate the binding energies E_{ex} and absorption coefficient α_{ex} of these excitonic transitions as functions of the applied voltage and period of the induced superlattice potential. A competition between confinement and Coulomb attraction produce strong oscillations on E_{ex} and α_{ex} which should be observed experimentally.

I. Introduction

Optical and electronic properties of artificial materials such as heterostructures and superlattices have attracted the attention of many publications. Special interest has been paid to the excitonic transitions in single, double coupled and multiple quantum wells, both theoretical and experimentally[1]. Quantum confinement as well as the effects of the applied electric and magnetic fields have demostrated to significantly affect the binding energies and the absorption coefficients of excitons in these systems. On the other hand, very recent experimental studies[2] of the optical properties of quantum wells with a field-effect-induced lateral superlattice potential have shown that the luminescence and luminescence excitation spectra exhibit a strong dependence on the applied voltages. Further investigations on these type of systems have demostrated[3] potential possibilities of applications in electro-optic devices. Since it is experimentally possible to produce a periodic electric-field modulation to confine laterally electrons and holes we explore, in this report, the effects of a periodic gate potential on excitonic transitions in single quantum wells of the type I heterostructures (the electrons and holes are confined within the same layer). We use the variational method and the tight binding approach to estimate the energies E_{ex} and absorption coeficient α_{ex} of quasi-1D excitonic transitions as function of the periodicity and the potential strength. To be precise, we model a quantum-well structure GaAs-AlGaAs with a corresponding periodic gate potential. The excitons are confined in the z-direction by a quanturn well of width a_3 (structural confinement), in the x-direction by a periodic gate potential (electrostatic confinement) and they are free to move in the y-direction.

We use the effective mass theory for the hamiltonian of electrons and holes, the envelope function method and a familiar variational approach[4,5] to solve the Schroedinger equation and calculate E_{ex} and α_{ex}. The variational exciton wave function is written as the product of a function depending on the relative coordinates of the system, and the single-particle wave functions of the individual electron and hole appropriate for the specific geometry of interest, taking into account the periodicity of the induced superlattice. The resulting generalized eigenvalue problem is then solved in the tight binding approach. In the limit of strong electrostatic confinement, the situation studied here resembles the excitons in type II superlattices[7], where the electron and hole are confined in spatially separated wells. In the effective mass theory and neglecting any band nonparabolicity, as we deal with typically small excitonic energies, the hamiltonian of the excitons in the periodic potential under study can be written as

$$H = T - \frac{e^2}{\epsilon|\vec{r}_e - \vec{r}_h|} + U(z_e, z_h) + U(x_e, x_h), \qquad (1)$$

where T is the kinetic energy operator for the electron and hole, ϵ is the static dielectric constant, $\vec{r}_e$ and $\vec{r}_h$ are the electron and hole coordinates, $U(z_e, z_h) = U_e(z_e) + U_h(z_h)$ is the quantum structural confinement and $U(x_e, x_h) = U_e(x_e) + U_h(x_h) = \Sigma V_e(x_e - md) + \Sigma' V_h(x_h - s_m)$ is the periodic electrostatic confinement, $s_m = m(1 - |m|/2)d$, $m \neq 0$. To calculate E_{ex} and α_{ex} with the above hamiltonian we follow a procedure similar to that used by Dignam and Sipe for type II superlattices[4]. Using the single-well hamiltonian H_l^0, with the appropriate x-axis origin, we write the full hamiltonian as

$$H = H_l^0 + \Delta U_l^0(x_e, x_h), \qquad (2)$$

where $\Delta U_l^m = U_e(x_e) + U_h(x_h) - V_e(x_e - s_l - m_d) - V_h(x_h - md)$, with the potential

$$V_\sigma(x_\sigma) = \begin{cases} -v_\sigma, & |x_\sigma| \leq d_\sigma/2 \\ 0, & \text{otherwise.} \end{cases} \qquad (3)$$

This procedure allows one to deal with a single variational parameter, but with an overall wave function which is adapted well to the physical problem at hand. The variational wave function is then written as $\Psi(\vec{r}_e, \vec{r}_h) = e^{iK_yY}(\Phi(r, z_e, z_h, x_e, x_h)$. Since Φ is periodic on x, we may write the solution in terms of Wannier functions W_n as

$$\Phi(r, z_e, z_h, x_e, x_h) = \frac{1}{N^{1/2}} \sum e^{iqmd} W_n(r, z_e, z_h, x_e - md, x_h - md). \qquad (4)$$

Then we obtain the generalized eigenvalue equation

$$H_{ij}^q b_j^n = E_n A_{ij}^q b_j^n \ , \qquad (5)$$

where A_{ij}^q and H_{ij}^q are matrix elements given in Ref. [4]. Finally, we obtain the binding energy $E_{ex} = E_{free} - E_n(q)$, with E_{free} being the energy of the noninteracting particles but still confined, and the absorption coefficient as $\alpha_n = \sum_q |\int dX e^{ikX} \Phi_n^q(r = 0, z = 0, x = 0)|^2$ [4,6]. The parameters used for the actual calculations correspond to a GaAs-AlGaAs heterostructure, so that we take, $m_e = 0.067m_0$, $\epsilon = 12.2$, and for the heavy hole mass $m_h^H = 0.377m_0$ [1]. Here only heavy holes are considered. To examine the effects of the lateral electrostatic confinement, we calculate the binding energies E_{ex} [8] and the absorption coefficient α_{ex} of the excitonic transitions as functions of the superlattice period $d = d_w + d_b$ varying the well-width d_w for different values of the barrier-width d_b. The superlattice potential for electrons is given by Eq. (3) and correspondingly, the effective potential for holes is $V^h(x_h) = -V^e(x_e \to x_h)$, as the source of the modulation is electrostatic and only the sign is different for both carriers, and we consider $V^e = 10Ry^*$. Typical results for E_{ex} and α_{ex} versus the electron well-width are shown in Fig. 1. As we deal with type I heterostructures, the electron and hole coexist in the same layer, but the lateral electrostatic confinement resembles a type II superlattice. Under this conditions, the system exhibits stronger binding for smaller d_b and diminishes as the width of the induced potential well increases. Correspondingly, the absorption coefficient decreases rapidly for weaker binding in as much as an order of magnitude. As the excitons are less confined by the potential, negative binding energies may appear as a result of an increase in the kinetic energy that overtakes on the energies in the potential wells and that of Coulomb interaction[4]. For completeness, we have also studied the dispersion relation of the excitonic transitions. The excitonic band width (not presented here) shows a strong dependence on the confinement, is larger ($\sim$ 0.06meV) for smaller superlattice periods and is drastically decreased as the electrostatic confinement decreases.

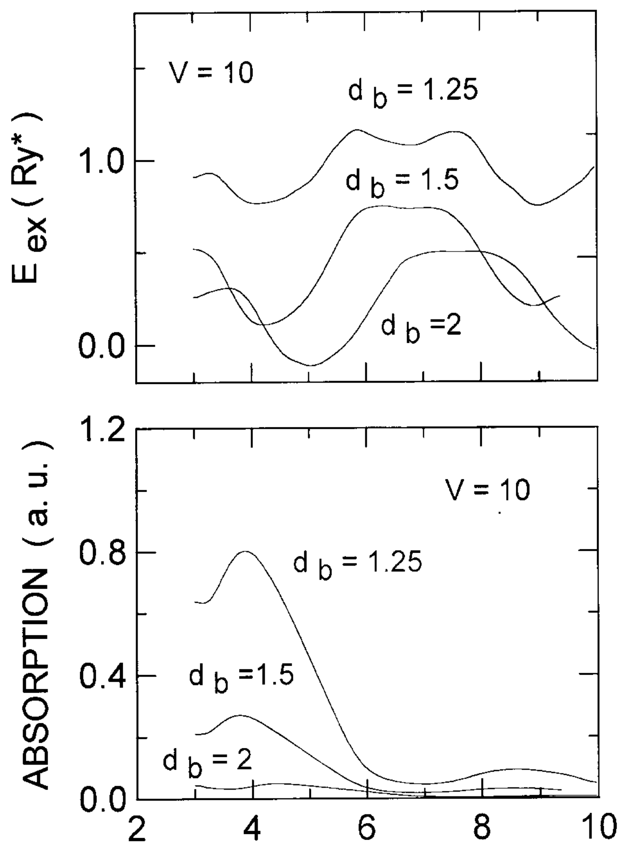

Figure 1. Binding energy E_{ex} (upper panel) and absorption coefficient α_{ex} (lower panel) versus well-width d_w for various d_b values as shown (in units of a_0).

In conclusion, we have studied the influence of the induced lateral electrostatic superlattice on the optical properties of quasi-1D excitons in quantum wells. We find that the energies and absorption coefficient are strongly modified with respect to those of the free excitons. As the barrier increases its width or size the exciton polarizes, electron and hole separate, E_{ex} and α_{ex} decrease significantly. Moreover, for intermediate values of the parameters, we find strong oscillations of these quantities as d_w is varied, which are consequence of the competition between Coulomb interaction and confinement effects.

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References

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