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INFLUENCE OF SCREENING AND ELECTRIC FIELD ON EXCITON BINDING ENERGY IN ASYMMETRIC DOUBLE QUANTUM WELL

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The influence of screening by confined free electrons on the exciton binding energy in the asymmetric double quantum well is calculated for various values of applied electric field perpendicular to the layer plane. The dependence of the exciton binding energy on carrier concentration is found to be stronger for lower than for higher fields. The drop of field-dependent exciton energy is less remarkable at higher densities of free electrons. Calculations were performed at 10 and 300 K, and up to densities of 10^{14} m^{-2} and 7×10^{14} m^{-2}, respectively.

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Sufficient knowledge of excitonic properties of semiconductor heterostructures is necessary for correct evaluation of their optical properties. Excitonic effects should be included also in models of the electric field dependence of optical absorption, especially at optical band edge.

In the present paper we calculate screened exciton binding energy in asymmetric double quantum well (ADQW) subjected to perpendicular electric field. Screening is caused by free electrons originating from modulation doping. The electric field changes the position and occupation of subbands in ADQW, therefore in our calculation — unlike [1] — we take into account the two lowest subbands. We treat the effect of screening within the framework of linear response formalism and assume that electrons in both subbands obey Fermi–Dirac statistics. The densities of the screening carriers will not be too high, and therefore such many-body processes as phase space occupation and gap renormalization have not to be considered.

For our investigation of the influence of screening of carriers on exciton binding energies we have chosen the approach of Stern and Howard [2]. The two-dimensional Fourier transform of the Poisson equation for a point hole at the position $r_{\rm h} = (0, 0, z_{\rm h})$ is

$$\left(\frac{\partial^2}{\partial z_{\rm e}^2} - Q^2\right) V(Q, z_{\rm e}, z_{\rm h}) = -\frac{e}{\varepsilon_{\rm s}}\delta(z_{\rm e} - z_{\rm h}) - \frac{1}{\varepsilon_{\rm s}}\rho^{\rm ind}(Q, z_{\rm e}), \tag{1}$$

where $\rho^{\rm ind}$ is the induced charge due to the presence of other carriers, $z_{\rm e}$ is the electron coordinate. Using the Green function and the Fourier transform of $\rho^{\rm ind}$, one obtains the following integral equation for $V(Q, z_{\rm e}, z_{\rm h})$ [2, 3]

$$V(Q,z_{\rm e},z_{\rm h})=\frac{e}{2\varepsilon_{\rm s}Q}{\rm e}^{-Q|z_{\rm e}-z_{\rm h}|}$$
$$-\sum_{i=1}^{n}\frac{Q_i}{Q}\int_{-\infty}^{\infty}{\rm d}z''\psi_i^2(z''){\rm e}^{-Q|z_{\rm e}-z''|}\int_{-\infty}^{\infty}{\rm d}z'\psi_i^2(z')V(Q,z',z_{\rm h}) \tag{2}$$

with $Q_i = 2\left(e^2m_{\rm e}^*/4\pi\varepsilon_{\rm s}\hbar^2\right)f_i(k=0)$, where i labels subbands contributing to screening. ψ_i are wave functions of electrons in the i-th subband.

It was found [4] that for low fields the particle with the ground-state energy $E_{1\rm e}$ is localized in the wider well, and the one with the first excited-state energy $E_{2\rm e}$ sits in the narrower well. Because of the heavy-hole ground-state $E_{1\rm hh}$ being localized (for all fields F) in the wider well, the exciton $E_{1\rm e1hh}$ will be spatially direct (electron and hole in the same layer). With increasing electric field, the particles get delocalized until the ground state $E_{1\rm e}$ becomes localized in the narrower well and the exciton $E_{1\rm e1hh}$ becomes indirect. Since at certain values of the field the energy difference between $E_{1\rm e}$ and $E_{2\rm e}$ is very small, we take in the calculation of exciton binding energies both subbands into account ($n = 2$).

The solution of Eq. (2) can be found after simple manipulations

$$V(Q,z_{\rm e},z_{\rm h})=\frac{e}{2\varepsilon_{\rm s}Q}\left[{\rm e}^{-Q|z_{\rm e}-z_{\rm h}|}-Q_1A_1(z_{\rm e})K_{11}A_1(z_{\rm h})-Q_1A_1(z_{\rm e})K_{12}A_2(z_{\rm h})\right.$$
$$\left.-Q_2A_2(z_{\rm e})K_{21}A_1(z_{\rm h})-Q_2A_2(z_{\rm e})K_{22}A_2(z_{\rm h})\right], \tag{3}$$
$$K_{11}=D(Q+Q_2H_{22}),\qquad K_{12}=-DQ_2H_{12},$$
$$K_{21}=-DQ_1H_{12},\qquad K_{22}=D(Q+Q_1H_{11}),$$
$$D=\left[(Q+Q_1H_{11})(Q+Q_2H_{22})-Q_1Q_2H_{12}^2\right]^{-1},$$
$$H_{ij}=\int_{-\infty}^{\infty}{\rm d}z''\psi_i^2(z'')\int_{-\infty}^{\infty}{\rm d}z'\psi_j^2(z'){\rm e}^{-Q|z'-z''|},$$
$$A_i(z_{\rm e})=\int_{-\infty}^{\infty}{\rm d}z''\psi_i^2(z''){\rm e}^{-Q|z_{\rm e}-z''|}.$$

Equation (3) is a special simple form (static long-wavelength limit) of the inversion of the dielectric matrix (Lindhard form) in sublevel space. This approximation should work well for not too high densities.

The exciton binding energy can be found by minimizing the expression [5]

$$E_{\rm B}=\frac{\hbar^2}{2\mu^*\lambda^2}$$
$$-\frac{4e}{\lambda^2}\int_{z_{\rm e}}{\rm d}z_{\rm e}\psi_{\rm e}^2(z_{\rm e})\int_{z_{\rm h}}{\rm d}z_{\rm h}\psi_{\rm h}^2(z_{\rm h})\int_0^{\infty}{\rm d}r\,rV_{\rm e-h}(r,z_{\rm e},z_{\rm h})\exp\left(-\frac{2r}{\lambda}\right) \tag{4}$$

with respect to λ. $V_{\rm e-h}(r, z_{\rm e}, z_{\rm h})$ is the Fourier transform of $V(Q, z_{\rm e}, z_{\rm h})$, Eq. (3). Wave functions and energies of bound states are calculated numerically [6, 4].

The values of Q_i are $Q_i = \left(e^2m_{\rm e}^*/2\pi\varepsilon_{\rm s}\hbar^2\right)\{1+\exp[\beta(\mu(n_{\rm s},T)-E_i)]\}^{-1}$.

The ADQW considered consists of a GaAs wide well, a thin $Al_xGa_{1-x}As$ ($x \simeq 0.3$) barrier and a GaAs narrow well. Their thicknesses were chosen as $L_W = 78$ Å, $L_B = 55$ Å, and $L_N = 35$ Å, respectively. In the GaAs material $V(z) = 0$, in AlGaAs $V_c(z) = 240$ meV (conduction band), $V_v(z) = 160$ meV (valence band). As usual, the electron and hole effective masses ($m_e^* = 0.067m_0$ and $m_h^* = 0.45m_0$, respectively) are taken as the same for both materials.

Excitons exist up to a critical pair (Mott) density, n_c [7]. At low temperatures the Mott density is approximately 8×10^{14} m^{-2}; at 300 K it is about an order of magnitude higher (Fig. 6, Ref. [8]). In our calculations the concentration of electron–hole pairs n_s was always smaller than the critical density n_c.

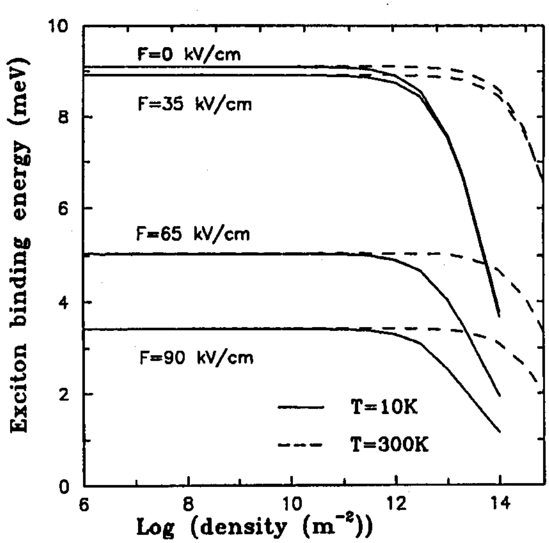

Fig. 1. Exciton binding energy vs. density of free electrons for various values of the applied electric field: $T = 10$ K (full lines), $T = 300$ K (dashed lines).

Figure 1 shows the dependence of the exciton binding energy E_{1e1hh} on the electron density for various electric-field values. It is evident that the exciton energy sharply drops for large densities. The relative decrease is largest for the zero field, while for stronger fields the drop is less remarkable. It is clear that the presence of a higher number of electrons influences the electron–hole interaction to a larger extent, the potential energy is more "screened" and the exciton binding energy decreases. When the electric-field strength increases, another effect plays a role — the electron eigenfunction in DQW becomes more smeared (delocalized) [4]. Therefore the exciton energy starts to decrease considerably already at small densities. The decrease in the exciton energy with increasing electron density is more moderate at high temperature.

In Fig. 2 the electric field dependence of the exciton energy is shown for various electron densities. A sharp decrease in the exciton energy is observed at such values of the electric field strength at which the exciton character is changed

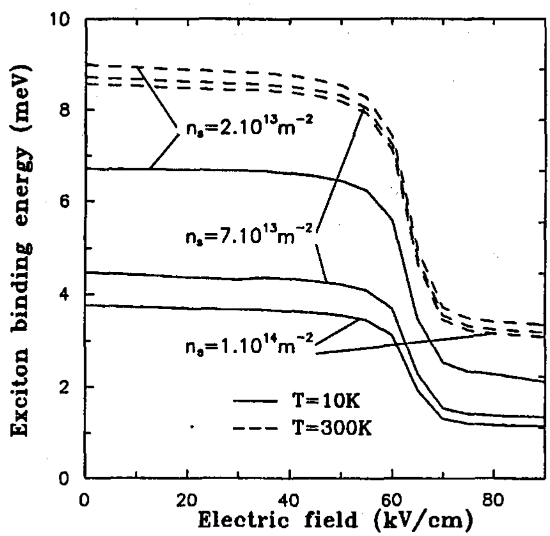

Fig. 2. Electric field dependence of exciton binding energy for various electron densities: $T = 10$ K (full lines), $T = 300$ K (dashed lines).

from direct to indirect one. Indirect excitons are formed by an electron and hole that are spatially separated, their Coulombic interaction is weak and therefore the exciton binding energy is small. The higher is the density of screening carriers, the smaller is the binding energy even for direct excitons and the sizeable difference between binding energies of direct and indirect excitons disappears.

We expect that also in undoped materials exciton binding energies are significantly influenced by screening of free carriers photogenerated in cw optic measurements. To estimate the effect quantitatively, one has to include not only screening by electrons, but that by holes as well. We will return to this problem in a future publication.

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