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The lifetime of quasi-free exciton magnetic polaron in a quantum well with semimagnetic barriers

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Abstract: The calculation of the radiative lifetime of a localized exciton confined in a quantum well is performed for CdTe/(Cd,Mn)Te structure where the quasi-free exciton magnetic polaron can be formed. There is shown that the polaron induced squeezing of the in-plane exciton localization radius leads to the increase of the lifetime. The lifetime dependence on the quantum well width is found to be altered by the polaronic effect in very thin CdTe/(Cd,Mn)Te quantum wells.

1. Introduction

The radiative lifetime of low-dimensional excitons has been a subject of theoretical and experimental studies during the recent decade⁽¹⁻¹¹⁾. The cases of free two and one-dimensional excitons are substantially described theoretically^(1,2) as well as the case of a bound zero-dimensional exciton^(3,4).

The time-resolved photoluminescence spectroscopy being a direct way to measure the exciton radiative lifetime has been applied to study exciton states in various quantum wells⁽⁷⁻¹¹⁾. The problem of adequate theoretical description of these experiments arises since there are not free but localized exciton states seen in the photoluminescence. The lifetime of the localized excitons is usually strongly different from that of free ones and depends, moreover, on the shape of the localization potential.

The subject of this paper is to study the localized exciton lifetime in semimagnetic heterostructures, where the exciton magnetic polaron (EMP) can be formed. The experimental studies of the dependence of τ on the quantum well (QW) width⁽⁷⁻¹¹⁾ reveal its strong deviation in different heterostructures. Following Ref. 7, it can be explained by the different values of the exciton Bohr radius in the studied materials. The simple calculation⁽⁷⁾ shows that τ is proportional to the exciton area (squared exciton Bohr radius) divided by the area of the exciton in-plane localization. The exciton in-plane Bohr radius, $a_{\perp}$, is a nonmonotonic function of the QW width, L_z . The corresponding variations of τ with L_z have been observed in GaAs/AlGaAs⁽⁷⁾ and InP/InGaAs^(8,9) QWs. The exciton Bohr radius appeared to be much less dependent on L_z in wide gap II-VI heterosystems because of the higher electron and hole effective masses. This is a reason, probably, why very slight dependence of τ on L_z has been observed in CdTe/CdZnTe and CdTe/CdMnTe quantum wells^(10,11). To our knowledge, however, there are still no data on τ behaviour in ultrathin CdTe/CdMnTe QWs where the exciton magnetic polaron (EMP) can be formed^(12,13).

The purpose of this work is to study an effect of exchange induced in-plane squeezing of the exciton wave function on the radiative life time in QWs with semimagnetic barriers, i.e. the EMP effect on τ . In this sense we shall consider the

polaron induced changes of the exciton localization area with L_z variation - an effect which could be strong in semimagnetic systems (12,13). We will show that the magnetic polaron effect can cause the dramatic increase of the exciton radiative life time in very thin CdTe/(Cd,Mn)Te QWs.

2. Theory

Let us consider the exciton localized on an island of the QW width fluctuation in single QW with semimagnetic barriers like CdTe/(Cd,Mn)Te. Since the exciton is localized, we shall use the general formulation for the lifetime, τ of zero-dimensional excitons obtained in Refs. 3-6. As follows from Refs. 5,6 :

$$\tau = 3 \left[\omega_{LT} (ka_B)^3 \left(\int \phi(\vec{r}_e, \vec{r}_h) \delta(\vec{r}_e - \vec{r}_h) d\vec{r}_e d\vec{r}_h \right)^2 \right]^{-1}, \quad (1)$$

where ω_{LT} and a_B are the oscillator strength and Bohr radius of an exciton in bulk well material: $k = \sqrt{\epsilon_B \omega / \epsilon_B}$ is the dielectric constant supposed to be equal in well and barrier materials : ω is the frequency of excitonic resonance : $\phi(r_e, r_h)$ is the exciton wave function, r_e, r_h are the radius vectors of electron and hole.

Let us now discuss separately two limiting cases of the exciton in-plane localization: i) the case of independent electron and hole localization, ($R_0 \ll a_B$) and ii) localization of an exciton as whole particle ($R_0 \gg a_B$), where R_0 is the typical size of the localization potential, a_B is the exciton Bohr radius.

In the former case, the exciton wave function can be represented as :

$$\phi(\vec{r}_e, \vec{r}_h) = f_e(\rho_e) f_h(\rho_h) U_e(z_e) U_h(z_h) \quad (2)$$

where $f_{e(h)}(r_{e(h)})$ and $U_{e(h)}(z_{e(h)})$ are the electron (hole) envelope functions in and normal to the QW plane, respectively. Choosing $f_{e(h)}$ in exponential form, one can obtain from (1) :

$$\tau = 3 \left[\omega_{LT} (ka_B)^3 I_{eh}^2 \frac{16 \rho_{oe}^2 \rho_{oh}^2}{(\rho_{oe} + \rho_{oh})^4} \right]^{-1}, \quad (3)$$

where

$$I_{eh} = \int_{-\infty}^{\infty} U_e(z) U_h(z) dz.$$

$\rho_{oe(h)}$ is an electron (hole) Bohr radius. In the case of exciton localization as a whole particle $\phi(r_e, r_h)$ can be written as :

$$\phi = F(\vec{R}) f(\vec{\rho}) U_e(z_e) U_h(z_h) \quad (4)$$

where F is the exciton in-plane envelope function, f is a function of electron-hole relative motion, R is the exciton centre of mass coordinate, $\rho = \rho_e - \rho_h$.

For exponential $F(R)$ and $f(\rho)$ one can obtain:

$$\tau = 3 \left[\omega_{LT} (ka_B)^3 I^2 \frac{16 L^2}{a_1^2} \right]^{-1}. \quad (5)$$

The values of τ obtained in the approximation of exciton localized as whole particle are much smaller than that for the case of independently confined electron and hole because of the factor $(a_1/L)^2$, which is much smaller than unity in this case. It is seen now that in the case of exciton localization as a particle the dependence of τ on the QW width is given by factor $\frac{a_1^2}{L^2}$ in line with Ref. 7. On the other hand, if electron

Fig. 1. - Exciton and hole in-plane localization radius R_f as function of the QW width (solid lines 1 and 2, respectively). R_0 is the radius of an island of QW width monolayer fluctuation. Free exciton in-plane Bohr radius, a_1 , is shown by the dashed line. Inset shows the squared electron-hole overlap integrand I_{eh}^2 as function of QW width.

Fig. 2. - Exciton radiative lifetime, τ as function of QW width, L_z . Solid and dashed lines correspond to the case of exciton localization as a whole particle, dashed-dotted line - to the case of the independent electron and hole in-plane quantization. Curves 1 and 2 are calculated with exponential and Gaussian shape of the in-plane exciton wave functions. The corresponding dashed lines show the calculation of τ which do not account the magnetic polaron effect.

and hole are quantized separately, one has the more complicated factor (see Eq. 3), which is, moreover, dependent on the choosen shape of electron and hole in plane wave functions.

To take into account the exchange induced exciton squeezing during the EMP formation in general we should find the dynamics of the radius of exciton (hole) localization $L(\rho_{oh})$ in time. If the polaron formation time is larger or in order of the exciton life time one can expect the strongly nonexponential dependence of the exciton radiation intensity on time, so that τ as a parameter becomes hardly applicable to the system. That is why we shall limit ourself, for a while, by a consideration of the simplest case when the magnetic polaron formation time is much shorter than τ . In this limit, to account the polaronic effect one just has to substitute $L(\rho_{oh})$ in Eqs. (5.3) by the corresponding radius of the magnetic polaron ground state.

The ground state of two-dimensional quasi-free EMP in a QW with semimagnetic barriers has been calculated (12,13) by the variational solving of the Schroedinger equation for in-plane exciton (or hole) motion.

The difference between the cases of exciton localization as a whole particle and separate confinement of electron and hole consists in the different values of in-

plane mass and in-plane potential. The parameter R_0 , which governs the potential should be taken different for an exciton and for a hole in order to obtain the magnetic polaron energy in agreement with the experimental data.

3. Results and Discussion

In this part the developed approach will be applied to the well-studied CdTe/CdMnTe system. Fig.1 shows the magnetic polaron induced decrease of the exciton localization radius in thin CdTe/Cd_{0.75}Mn_{0.25}Te QWs calculated in the model of quasy-free EMP (12,13). We have used the parameters of the system from Refs.12,13 and the radius of initial exciton localization $R_0=85\text{\AA}$. Solid curves (1,2) represent the calculation with Gaussian and exponential trial functions, respectively. Dashed curve shows the calculation in a model of independent electron and hole quantization with $R_0=35\text{\AA}$. One can see that in all the analysed cases the radius of exciton localization decreases substantially in the range of QW widths $L_z < 30\text{\AA}$, where the polaron can be formed. Dashed-dotted curve in Fig. 1 represents the exciton in-plane Bohr radius behaviour with L_z . Inset shows the very smooth dependence of the electron-hole overlap integral on L_z .

The magnetic polaron induced decrease of the exciton localization area causes the sizeable enhancement of the exciton radiative life time, as Fig. 2 shows. The solid lines 1,2 represent the calculation of τ according to the Eq.5, i.e. for the cases of exciton localization as whole particle. The corresponding dashed lines show the calculated behaviour of τ , if the polaron induced changes of the exciton localization area are neglected. The comparison of solid and dashed curves shows that the EMP formation causes 3-4 times stronger enhancement of τ in very thin QWs than it is obtained from the variations of a_L . Dashed-dotted curve shows the exciton life time as function of L_z for the case of independent electron and hole in-plane quantization (Eq. 3).

The values of τ calculated in this model are of the same order as those calculated for bound zero-dimensional excitons (3,4). On the other hand, the experimentally measured exciton radiative life time in thick CdTe/CdMnTe QWs is about 150 ps (11), which clearly shows that the model of exciton in-plane localization as a particle much better corresponds to the experimentally studied samples.

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