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Measurement of exciton lifetime in double semimagnetic quantum well by means of magneto-optical Kerr effect

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Magneto-optical Kerr effect caused by weak oscillating magnetic field in Faraday geometry was used for measuring of the exciton radiative Γ_0 and nonradiative Γ damping rates in semimagnetic quantum well $Cd_{0.984}Mn_{0.016}Te$, separated from more wide nonmagnetic quantum well CdTe by tunnel-transparent barrier. Measured values in energetic units were found to be $\hbar\Gamma_0 \approx 114\,\mu$eV and $\hbar\Gamma \approx 4.6$ meV. Large value of Γ means that the time of carriers tunneling from narrow well to wide one is shorter than 0.1 ps.

Keywords: semimagnetic semiconductor nanostructures, magneto-optical Kerr effect.

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1. Introduction

Exciton effects have significant influence on optical properties of quantum-size semiconductor structures, and shall be considered when designing perspective devices of optoelectronics. The theory of exciton contributions into spectra of absorption, reflection and photoluminescence [1], whose key parameters are radiative, $\hbar\Gamma_0$, and nonradiative, $\hbar\Gamma$, broadening of exciton line, is well developed and confirmed by multiple experiments [1–5]. At the same time the experimental determination of the key parameters of the exciton resonances in specific structures can face significant difficulties. In particular, in double quantum wells (QWs) separated by a thin barrier, tunneling of photoexcited carriers from the narrow well to the wide one can lead to a significant reduction in the exciton lifetime [6] and broadening of the exciton resonance in the narrow well, which complicates the use of standard methods of spectroscopy of luminescence and reflection.

The present paper is devoted to measurement of the values of $\hbar\Gamma_0$ and $\hbar\Gamma$ in the narrow (8 nm) quantum well of $Cd_{0.984}Mn_{0.016}Te$, separated from the wider (20 nm) well of CdTe by the tunnel-transparent (1.6 nm) barrier of $Cd_{0.88}Mg_{0.12}Te$.

2. Structures and experimental procedure

The structure was grown by molecular beam epitaxy (MBE) on GaAs (100)-substrate. The buffer layer of $Cd_{0.88}Mg_{0.12}Te \approx 4\,\mu$m thick separates the wide well from the substrate. The narrow well, and, hence, entire structure is covered with the $Cd_{0.88}Mg_{0.12}Te$ layer 50 nm thick.

Recent studies of spectra of exciton reflection in isolated (single) QWs $A^{II}B^{VI}$ showed that radiative broadening $\hbar\Gamma_0$ practically does not depend on the well width and comprises several tens of μeV (see, for example, data for QW CdTe/CdZnTe in [5]). The value of the nonradiative broadening $\hbar\Gamma$ can change within a wide range depending on the experiment conditions. Specifically, the exciton scattering, associated with the dark exciton reservoir, is accompanied with an increase in $\hbar\Gamma$ up to several hundreds of μeV [5]. We can suppose that in a double QW this effect significantly reduces for excitons in the narrow well due to their migration to the wide well. On the other hand, the tunneling into the wide well itself shall lead to $\hbar\Gamma$ increasing due to decreasing of the effective lifetime of excitons, while the radiative broadening $\hbar\Gamma_0$ shall not significantly change.

It turned out to be impossible to experimentally check these assumptions by the methods usually used for this purpose, which are based on measuring the width of the exciton line in photoluminescence or transmission spectra. The matter is that photoluminescence from the narrow well is not observed due to rapid tunneling of photoexcited charge carriers into the wide well. The studied structure was grown on GaAs substrate, so it is not transparent within the wavelength range of the exciton resonance in the narrow well. Application of the standard method of reflection using the incandescent tungsten lamp radiation also was difficult, since the exciton resonance in the narrow well is strongly broadened due to the short lifetime of excitons, and the reflection spectrum of the structure is strongly distorted as a result of interference with light reflected from GaAs substrate (Figure 1).

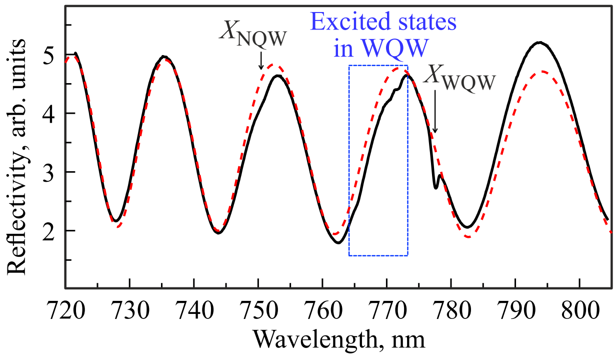

Figure 1. The reflection spectrum of the studied structure measured in zero magnetic field at temperature $T = 6\,\mathrm{K}$ (solid line). Vertical arrows indicate the resonance wavelength for excitons X_{WQW} and X_{NQW} in wide and narrow wells, dashed rectangle indicates the region of excited states in the wide well. The incandescent tungsten lamp was used as the light source. Dashed curve presents the reflection spectrum calculated using Eq. (3) considering dependence of refractive index on the epitaxial layer $\mathrm{Cd_{0.88}Mg_{0.12}Te}$ on the wavelength.

Therefore, to measure $\hbar\Gamma_0$ and $\hbar\Gamma$ we took advantage of the fact that the material of the narrow quantum well, $\mathrm{Cd_{0.984}Mn_{0.016}Te}$, is diluted magnetic (semimagnetic) semiconductor, and used the magneto-optical Kerr effect, which is effective to study the magnetization and determine parameters of excitons in structures based on diluted magnetic semiconductors [1,7]. The exchange interaction of the charge carriers with d-electrons of $\mathrm{Mn^{2+}}$ ions significantly increases splitting of spin states of carriers and excitons upon application of the magnetic field [7], which ensures registration of the magneto-optical effects even in weak magnetic fields $\sim 1\,\mathrm{G}$.

3. Results and discussion

The used method is based on the fact that measured in the Kerr effect small angle of rotation of linear polarization plane of reflected beam is $\theta = (I_1 - I_2)/2(I_1 + I_2)$, where I_1 and I_2 are intensities of reflected components, linear polarized at angles $+45^\circ$ and -45° to plane of polarization of incident light, which are simultaneously registered by photodiodes 1 and 2 being part of the balanced photodetector. Generally, the angle θ is small, so $I_1 \approx I_2$, and the effect of polarization-insensitive interference component of reflected light at the measured angle is significantly suppressed.

The Kerr effect occurs due to phase difference of the amplitude reflection coefficients (r_+) and (r_-) of light waves polarized in the right and left circles [1,8]. Under the conditions of our experiment, when the contribution of the exciton in the narrow quantum well to the total amplitude reflection coefficient of the structure $r_0 = (r_+ + r_-)/2$ is small, the Kerr angle is (see Chapter 3 in [1]):

$$\theta = -\mathrm{Im}\left[\frac{r_+ - r_-}{2r_0}\right]. \tag{1}$$

When calculating r_0 we can neglect the quantum well contribution and consider only reflection from the structure surface and from heterointerface with the substrate. As a result considering Eq. (3.242) in paper [1] we obtain

$$r_0 = -\frac{n-1}{n+1}\,\frac{1 - \frac{n+1}{n-1}|r_m|\exp(2i\varphi_{m0} + i\varphi_m)}{1 - \frac{n-1}{n+1}|r_m|\exp(2i\varphi_{m0} + i\varphi_m)}, \tag{2}$$

where n is the refractive index of epitaxial layer $\mathrm{Cd_{0.88}Mg_{0.12}Te}$, $|r_m|$ and φ_m are absolute value and phase of reflection coefficient of the light wave from the boundary with substrate, $\varphi_{m0} = 2\pi nL/\lambda$ is the phase shift of the light wave when passing through the epitaxial layer of thickness L, λ is the light wavelength in vacuum. Accordingly, the reflectance is equal to

$$R = |r_0|^2 = \left(\frac{n-1}{n+1}\right)^2$$
$$\times\frac{1 + \left(\frac{n+1}{n-1}\right)^2|r_m|^2 - 2\,\frac{n+1}{n-1}|r_m|\cos(2\varphi_{m0} + \varphi_m)}{1 + \left(\frac{n-1}{n+1}\right)^2|r_m|^2 - 2\,\frac{n-1}{n+1}|r_m|\cos(2\varphi_{m0} + \varphi_m)}. \tag{3}$$

Fitting the spectral dependence of the intensity of light reflected from the structure (Figure 1) with this formula allows us to determine the values of $|r_m|$, φ_m and L.

The exciton contributions into the reflectance of structure for two circular polarizations [9,10] (see also Eq. (3.241) in Ref. [1]) are set by the following expression:

$$r_\pm = r_\pm^{ex}\,\frac{4n}{(n+1)^2}\exp(2i\varphi_w)$$
$$\times\left(\frac{1 + |r_m|\exp(2i\varphi_{mw} + i\varphi_m)}{1 - \frac{n-1}{n+1}|r_m|\exp(2i\varphi_{m0} + i\varphi_m)}\right). \tag{4}$$

Here $r_\pm^{ex}(\omega) = i\Gamma_0/[\omega_{0,\pm} - \omega - i(\Gamma_0 + \Gamma)]$, ω is the light wave frequency, $\omega_{0,\pm}$ are frequencies of exciton resonance for right and left polarized components, Γ_0 and Γ are radiative and nonradiative broadening of exciton level, φ_w is the phase shift of light wave reflected from the quantum well on the way from QW middle to structure surface, φ_{mw} is the phase shift of light wave in path between the heteroboundary with substrate and quantum well [1]. In magnetic field B, applied in Faraday geometry, $\omega_{0,\pm} = \omega_0 \mp (\omega_e + \omega_h)/2$, where splitting of the exciton level is composed by magnetic field induced splittings of electron and hole levels $\hbar\omega_e$ and $\hbar\omega_h$ and equals $\hbar(\omega_e + \omega_h) = \hbar AB$. In semimagnetic semiconductor, the value of A is determined by $s/p{-}d$ exchange interaction of electrons and holes with manganese ions and, in the linear magnetic field approximation, is

$$A = \frac{(P_e\alpha N_0 - P_h\beta N_0)}{\hbar}\cdot\frac{S(S+1)}{3}\,x_{\mathrm{eff}}\,\frac{g_{\mathrm{Mn}}\mu_B}{k_{\mathrm{B}}(T + T_0)}, \tag{5}$$

where $\alpha N_0 = 0.22\,\mathrm{eV}$ and $\beta N_0 = -0.88\,\mathrm{eV}$ are constants of exchange interaction of electrons and holes with manganese ions, $S = 5/2$ and $g_{\mathrm{Mn}} = 2$ are spin and g-factor

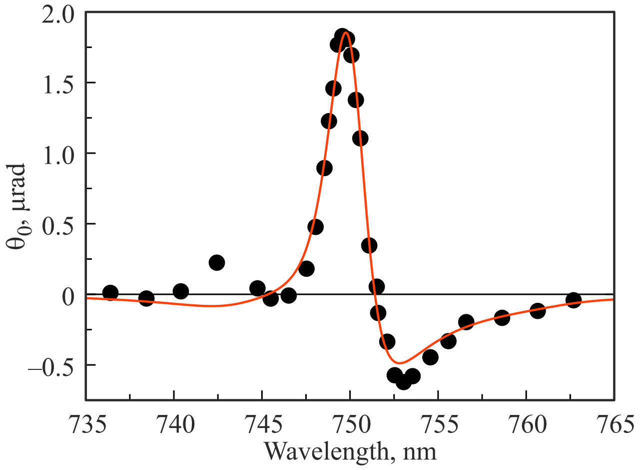

Figure 2. Experimental (circles) and calculated (solid curve) spectral dependences of Kerr angle amplitude in the range of exciton resonance in semimagnetic quantum well in longitudinal magnetic field $B(t)=B_1\cos(\Omega t)$ at $B_1=0.8$ G, $\Omega=130$ Hz and temperature $T=6$ K.

of Mn ion, $T_0=0.54$ K and $x_{\text{eff}}\approx[0.265\exp(-43.34x)+0.735\exp(-6.19x)]x=0.013$ are phenomenological parameters considering antiferromagnetic exchange interaction of manganese ions [7], $x=0.016$ is the content of manganese in semimagnetic well. Values of integrals of overlap of squares of wave functions of electron and hole with semimagnetic well $P_e=0.71$ and $P_h=0.73$ were obtained by numerical calculation, which considered both quantum-size potential of structure [11], and Coulomb interaction of electron and hole. Parameters of semiconductor layers are taken from Ref. [12].

To increase the measurement sensitivity we used an alternating magnetic field $B(t)=B_1\cos(\Omega t)$ and lock-in detection. In this case $\theta(\omega,t)=\theta_0(\omega)\cos(\Omega t)$, where, if condition $\Gamma_0\ll\Gamma$ is met,

$$\theta_0(\omega)=\frac{2n|D|}{n^2-1}\,\mathrm{Im}\left\{\frac{i\Gamma_0AB_1\exp[2i\varphi_w+\arg(D)]}{(\omega_0-\omega)^2-\Gamma^2-2i\Gamma(\omega_0-\omega)}\right\}. \qquad (6)$$

Here the dimensionless complex multiplier

$$D=\frac{[1+|r_m|\exp(2i\varphi_{mw}+i\varphi_m)]^2}{\left[1-\frac{n-1}{n+1}|r_m|\exp(2i\varphi_{m0}+i\varphi_m)\right]\times\left[1-\frac{n+1}{n-1}|r_m|\exp(2i\varphi_{m0}+i\varphi_m)\right]} \qquad (7)$$

accounts for reflection from the substrate.

Spectral dependence of amplitude of Kerr angle $\theta_0(\omega)$, measured in range of exciton resonance in semimagnetic quantum well in longitudinal magnetic field $B(t)=B_1\cos(\Omega t)$ at temperature $T=6$ K for $B_1=0.8$ G and $\Omega=130$ Hz is shown by circles in Figure 2. This dependence has noticeable resonance nature. Its approximation using Eq. (6) (solid curve) shows that energy of exciton resonance $\hbar\omega_0=1.6531$ eV, radiative broadening $\hbar\Gamma_0\approx114\,\mu$eV, and nonradiative broadening $\hbar\Gamma\approx4.6$ meV. At such a ratio of Γ_0 and Γ the observed resonance width is determined by nonradiative broadening, while the radiative broadening sets its amplitude.

Note that apparent width of exciton resonance can increase due to inhomogeneous broadening caused, for example, by technological fluctuations of quantum well width. But in single semimagnetic quantum wells of similar composition and the same temperature of crystal, the inhomogeneous broadening is $\hbar\Gamma_{inh}\sim0.7$ meV [13], which is almost an order of magnitude lower than measured by us value $\hbar\Gamma\approx4.6$ meV. Accordingly, we can neglect the effect of inhomogeneous broadening on width of resonance and values of parameters determined in our experiments. So, we can conclude, that in the studied structure with double quantum well the significant width of the exciton resonance in the narrow well is determined by quick tunneling of charge carriers into wide well with the characteristic time $\tau=1/2\Gamma\approx0.1$ ps.

4. Conclusion

Thus, we demonstrated the potential of the magneto-optical Kerr effect as a method for measuring the parameters of exciton resonance, including radiative and nonradiative lifetimes. The method allows one to study exciton states in structures with short nonradiative times, where traditional methods of spectroscopy of photoluminescence, transmission and reflection can not be applied or are ineffective.

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Conflict of interest

The authors declare that they have no conflict of interest.

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