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SPIN RELATED PHENOMENA IN NANOSTRUCTURES

Photon Echo from an Ensemble of (In,Ga)As Quantum Dots[1]

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Abstract—Photon echo from trions and excitons in (In,Ga)As/GaAs quantum dots was studied theoretically and experimentally. Theoretical analysis allowed us to distinguish between photon echo signals from excitons and trions measured in the same range of wavelength using different polarization configurations of laser excitation. The theoretical predictions are in good agreement with the experimental data.

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1. INTRODUCTION

The interaction between material excitations (excitons and trions) in semiconductor nanostructures and light can be very effective due to high oscillator strength of the excitations. Recently it was found that using the photon echo (PE) technique, one can transfer an information contained in the optical field into a spin system where it is decoupled from the optical field and may persists for a long time [1].

Semiconductor quantum dots (QDs) are considered to be promising for storing an information about the optical excitation since spin relaxation of electrons and holes in these nanostructures is characterized by significantly long times [2]. The inhomogeneity of the QD ensemble and spectral overlap of the exciton and trion transitions hamper investigations and analysis of these structures.

Here we describe the theoretical model developed for the photon echo signal from exciton ensemble in (In,Ga)As/GaAs QDs. Theoretical results complemented by the results for trions from [1] are compared with experimental data.

2. EXPERIMENTAL

We study the dynamics of PE from an ensemble of the (In,Ga)As/GaAs semiconductor QDs excited by the picosecond laser pulses.

The experiment was carried out on a sample with a single layer of (In,Ga)As QDs, which is inserted into a GaAs λ-microcavity. The QD density is 1.8×10^9 cm^{-2} and one of the GaAs barriers contains a Si δ-layer with donor density 8×10^9 cm^{-2}. More detailed description can be found in [3].

The experiment was performed in reflection geometry. The sample was placed into a helium bath cryostat and cooled down to about 2 K. A mode-locked Ti:sapphire laser was used as a source of the optical pulses with duration of about 2.5 ps and repetition rate of about 76 MHz.

In the experiment several polarization protocols has been used: the linear polarization of the optical pulses parallel to the QD axes x or y (z-axis is the structure grows axis) denoted in Fig. 1 as H and V, respectively, and the linear polarization parallel to the tilted 45° with respect to the x and y axes (denoted D and X, correspondingly). Transient PE signal was measured using heterodyne detection [4].

3. THEORETICAL MODEL

Let us consider optical excitation of the exciton ensemble by a short laser pulse with the frequency ω close to the resonant frequency ω_0. We assume rectangular shaped pulses of duration τ_p. According to the selection rules, the σ^+-circularly polarized light creates excitons with the projection of the angular momentum +1 on the direction of the light propagation and the σ^--polarized light creates excitons with the projection −1.

To describe the light-matter interaction and the exciton dynamics in magnetic field, we use a 5 × 5

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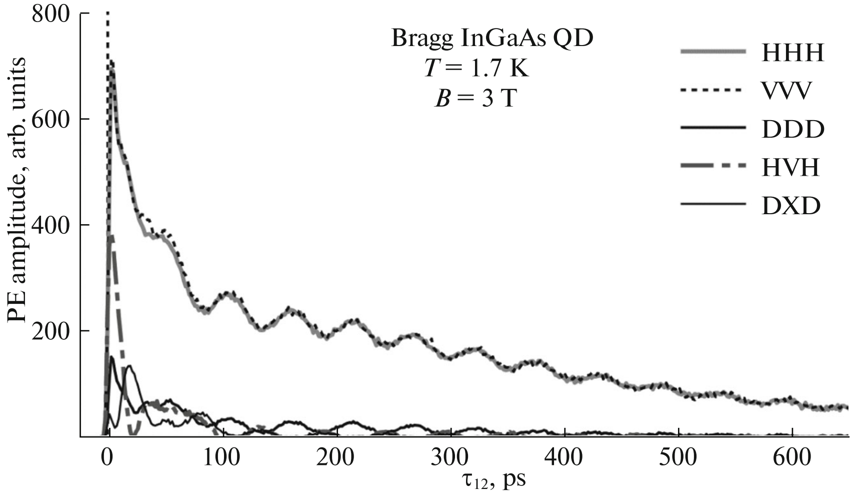

Fig. 1. The delay dependence of the PE signal. Symbols HHH etc. in the legend denote polarization of the first and second pulses and of the detected signal, respectively.

time-dependent density matrix written in the basis consisting of the ground state of the QD, two bright exciton states and two dark exciton states. The temporal evolution of the density matrix is described by the Lindblad equation:

$$i\hbar\dot{\rho} = \left[\hat{H}, \rho\right] + \Gamma. \qquad (1)$$

Here, $H = \hat{H}_0 + \hat{H}_B + \hat{V}$, $\hat{H}_0$ is the Hamiltonian of the unperturbed system, $\hat{H}_B$ is the Hamiltonian describing the interaction with magnetic field, and $\hat{V}$ describes the interaction with light.

In the calculations we assume that the duration of the laser pulse is significantly shorter than the exciton lifetime, the electron spin precession period in transverse magnetic field, and the times of decoherence. These assumptions allow us to separate the interaction of our system with light and its dynamics in magnetic field. Besides, for simplicity, we assume that g-factors are isotropic and the excitation is resonant, $\omega = \omega_0$.

4. RESULTS

The exciton PE signals for different polarization configurations are described by the following expressions:

$$P_{HHH}^{exc} \propto K\left[\cos^2(\Omega_p\tau_{12}) + \frac{\delta_0^2}{4}\frac{\sin^2(\Omega_p\tau_{12})}{\Omega_p^2}\right], \qquad (2)$$

$$P_{VVV}^{exc} \propto K\left[\cos^2(\Omega_m\tau_{12}) + \frac{\delta_0^2}{4}\frac{\sin^2(\Omega_m\tau_{12})}{\Omega_m^2}\right], \qquad (3)$$

$$P_{HVH}^{exc} = P_{VHV}^{exc} = 0, \qquad (4)$$

$$P_{DDD}^{exc} \propto \frac{1}{4}K\left[\left(\cos(\Omega_p\tau_{12}) + \cos(\Omega_m\tau_{12})\right)^2 + \frac{\delta_0^2}{4}\left(\frac{\sin(\Omega_p\tau_{12})}{\Omega_p^2} + \frac{\sin(\Omega_m\tau_{12})}{\Omega_m^2}\right)^2\right], \qquad (5)$$

$$P_{DXD}^{exc} \propto \frac{1}{4}K\left[\left(\cos(\Omega_p\tau_{12}) - \cos(\Omega_m\tau_{12})\right)^2 + \frac{\delta_0^2}{4}\left(\frac{\sin(\Omega_p\tau_{12})}{\Omega_p^2} - \frac{\sin(\Omega_m\tau_{12})}{\Omega_m^2}\right)^2\right], \qquad (6)$$

$$P_{HHH}^{tr} = P_{VVV}^{tr} \propto \frac{1}{4}K. \qquad (7)$$

And

$$\Omega_p \equiv \sqrt{(\omega_L^e + \omega_L^h)^2 + (\delta_0/\hbar)^2}, \qquad (8)$$

$$\Omega_m \equiv \sqrt{(\omega_L^e - \omega_L^h)^2 + (\delta_0/\hbar)^2}, \qquad (9)$$

$$K = \frac{if_1(f_2^*)^2\rho_{11}(0)\sin(\Omega_1\tau_p)(1 - \cos^2(\Omega_2\tau_p))}{\Omega_1\Omega_2^2}e^{-\frac{2\tau_{12}}{T_2}}. \qquad (10)$$

Here, ω_L and ω_L^h are electron and hole Larmor precession frequencies respectively, τ_{12} is the delay time between pulses, δ_0 is an isotropic exchange interaction constant. The exponential factor describes relaxation processes after the pulses action, ρ_{11} is the density matrix element corresponding to the exciton ground state population, and $f_\pm(t)$ is proportional to a smooth

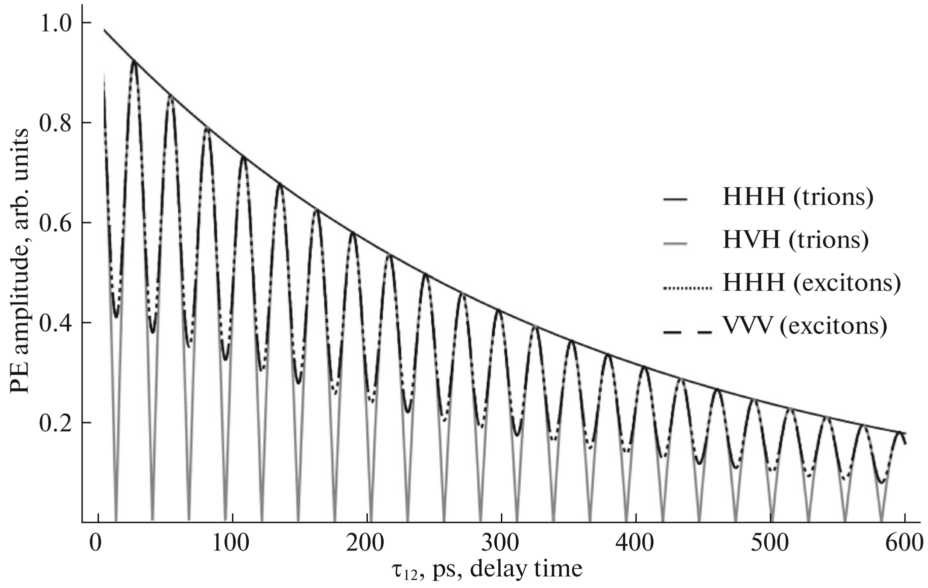

Fig. 2. Theoretically modeled PE signals for excitons and trions in the HHH, VVV, HVH polarization protocols. The black dotted and the black dashed overlapping lines demonstrate the HHH signal and VVV signals from excitons respectively, the black solid line demonstrates the HHH signal from trions, and the gray solid line demonstrates HVH signal from trions respectively. Parameters are: electron g-factor $|g_e| = 0.44$, magnetic field $B = 3$ T, the dephasing time $T_2 = 700$ ps, the isotropic exchange interaction constant for excitons is δ_0 and hole g-factor are assumed to be zero.

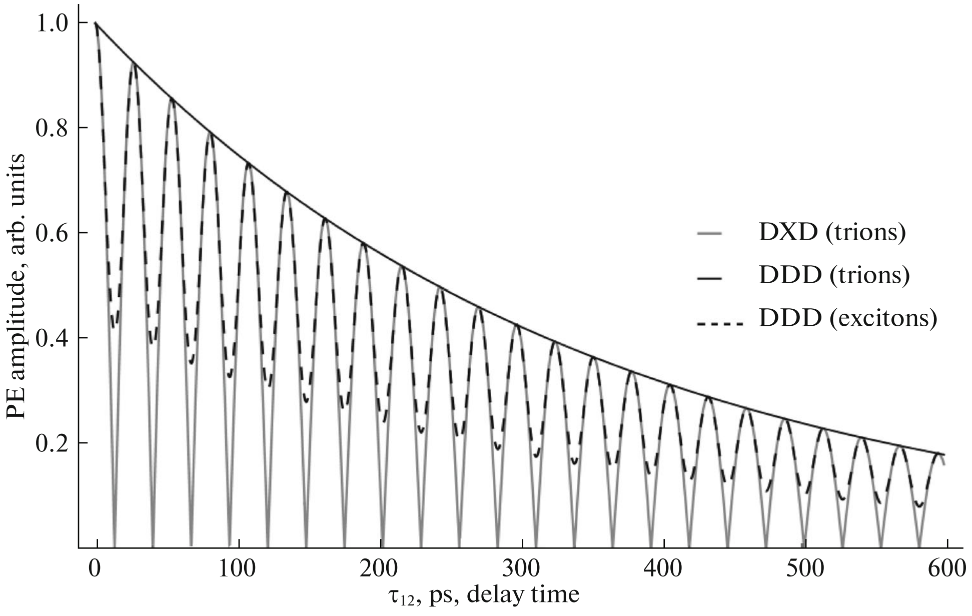

Fig. 3. Analytical results for the trion PE signal in the tilted polarizations. The black dashed line is the DDD exciton signal, the black solid line and the gray solid line are the DDD and DXD trion signals respectively. Parameters are the same as for Fig. 2.

envelopes of circular components σ^+ and σ^- of the exciting pulses. The areas of the first and the second pulses Ω_1 and; Ω_2 for the excitons

$$\Omega_1 \equiv \sqrt{|f_{+1}|^2 + |f_{-1}|^2}, \quad \Omega_2 \equiv \sqrt{|f_{+2}|^2 + |f_{-2}|^2}. \tag{11}$$

The trion PE signals for different polarization configurations can be obtained according to the theoretical model provided in [1]:

$$P^{tr}_{HVH} \propto K\cos((\omega^e_L - \omega^h_L)\tau_{12}), \tag{12}$$

$$P^{tr}_{VHV} \propto K\cos((\omega^e_L + \omega^h_L)\tau_{12}), \qquad (13)$$

$$P^{tr}_{DDD} \propto \frac{1}{4}K[\cos((\omega^e_L - \omega^h_L)\tau_{12}) + \cos((\omega^e_L + \omega^h_L)\tau_{12}) - 2\cos(\omega^e_L\tau_{12}) - 2\cos(\omega^h_L\tau_{12}) - 2], \qquad (14)$$

$$P^{tr}_{DXD} \propto \frac{1}{4}K\Big[\cos((\omega^e_L - \omega^h_L)\tau_{12}) + \cos((\omega^e_L + \omega^h_L)\tau_{12}) + 2\cos(\omega^e_L\tau_{12}) + 2\cos(\omega^h_L\tau_{12}) - 2\Big]. \qquad (15)$$

For the trions the pulses areas in the factor K are

$$\Omega_1 \equiv |f_1|, \quad \Omega_2 \equiv |f_2|. \qquad (16)$$

The theoretically obtained dependencies of exciton and trion PE signals on time delay are demonstrated in Fig. 2 and Fig. 3 (PE signals calculated in H and V polarizations are shown in Fig. 2, and PE signals calculated in D and X polarizations are shown in Fig. 3).

Theoretical analysis of the obtained dependencies for excitons and of the similar theoretical dependencies for trions described in [1] allows us to propose the polarization protocols of optical excitation to separate experimentally the contributions of the exciton and the trion PE signals. For example, in HHH configuration, the exciton signal has an oscillating character, while the trion signal has a decaying character without any oscillations (see Fig. 2). For the HVH configuration, the exciton signal is zero, while the trion signal shows cosine-like oscillations.

Similar behavior is observed for the DDD and DXD polarizations when $g_h = 0$: the exciton DDD signal is oscillating while the trion DDD signal is decaying; the exciton DXD signal is zero, while the trion DXD signal oscillates (see Fig. 3).

The comparison of the theoretically obtained results with the experimental data shown in Fig. 1 allows us to conclude that the oscillating parts of the PE signals measured in the VVV, HHH, and DDD configurations are caused by the exciton contribution, while the PE signals in the HVH and DXD configurations are due to the pure trion contribution.

It is worth to note that the presence of the trion contribution and the absence of the exciton contribution to the three-pulse PE signal in polarization configuration HVVH was discussed in [5]. However, dynamics in a magnetic field allows us to get a clearer picture.

5. CONCLUSIONS

The theoretical possibility of the experimental separation of the exciton and trion contributions in PE signal by appropriate choice of the exciting pulses polarization configurations have been shown in the present work. The most demonstrative separation of the exciton and trion contributions in the PE-signals on the sample with a close to a zero hole g-factor was analyzed.

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