26. PHOTON ECHO FROM AN ENSEMBLE OF (IN,GA)AS QUANTUM DOTS

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Photon echo from trions and excitons in (In,Ga)As/GaAs quantum dots has been studied theoretically and experimentally. Theoretical analysis allowed us to distinguish 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.

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 has been 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 persist 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.

In the present work 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 Ref. [1] are compared with the experimental data.

We study the dynamics of PE from an ensemble of the (In,Ga)As/GaAs semiconductor QDs excited by the picosecond laser pulses. Several polarization protocols have been used in the experiment: the linear polarization of the optical pulses parallel to the QD axes x or y (z-axis is the structure grows axis) denoted 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]. Experimental signals measured in different polarization configurations are shown in Fig. 1.
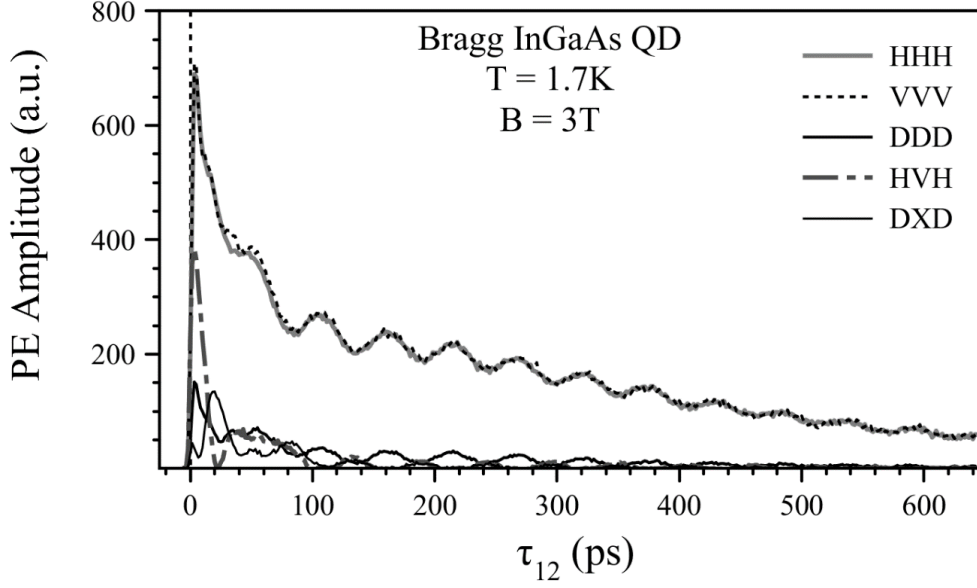
Fig. 1. The delay dependence of the experimental PE signals. Symbols HHH etc. in the legend denote polarization of the first and second pulses and of the detected signal, respectively

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

$$P_{HHH}^{exc} \propto e^{-\frac{2\tau_{12}}{T_2}} \left[cos^2(\Omega_p \tau_{12}) + \frac{\delta_0^2}{4} \frac{sin^2(\Omega_p \tau_{12})}{\Omega_p^2} \right], \tag{1}$$

$$P_{VVV}^{exc} \propto e^{-\frac{2\tau_{12}}{T_2}} \left[cos^2(\Omega_m \tau_{12}) + \frac{\delta_0^2}{4} \frac{sin^2(\Omega_m \tau_{12})}{\Omega_m^2} \right], \tag{2}$$

$$P_{HVH}^{exc} = P_{VHV}^{exc} = 0, \tag{3}$$

$$P_{DDD}^{exc} \propto \frac{1}{4} e^{-\frac{2\tau_{12}}{T_2}} \left[\left(cos(\Omega_p \tau_{12}) + cos(\Omega_m \tau_{12}) \right)^2 + \frac{\delta_0^2}{4} \left(\frac{sin(\Omega_p \tau_{12})}{\Omega_p^2} + \frac{sin(\Omega_m \tau_{12})}{\Omega_m^2} \right)^2 \right], \tag{4}$$

$$P_{DXD}^{exc} \propto \frac{1}{4} e^{-\frac{2\tau_{12}}{T_2}} \left[\left(cos(\Omega_p \tau_{12}) - cos(\Omega_m \tau_{12}) \right)^2 + \frac{\delta_0^2}{4} \left(\frac{sin(\Omega_p \tau_{12})}{\Omega_p^2} - \frac{sin(\Omega_m \tau_{12})}{\Omega_m^2} \right)^2 \right]. \tag{5}$$

Here

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

$$\Omega_m \equiv \sqrt{\left(\omega_L^e - \omega_L^h \right)^2 + (\delta_0/\hbar)^2}.$$

In the expressions above 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. Indices HHH etc. again

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denote polarization of the first and second pulses and of the detected PE signal, respectively.

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

$$P_{HHH}^{tr} = P_{VVV}^{tr} \propto \frac{1}{4} e^{-\frac{2\tau_{12}}{T_2}}, \tag{6}$$

$$P_{HVH}^{tr} \propto e^{-\frac{2\tau_{12}}{T_2}} \cos\left((\omega_L^e - \omega_L^h)\tau_{12}\right), \tag{7}$$

$$P_{VHV}^{tr} \propto e^{-\frac{2\tau_{12}}{T_2}} \cos\left((\omega_L^e + \omega_L^h)\tau_{12}\right), \tag{8}$$

$$P_{DDD}^{tr} \sim \frac{1}{4} e^{-\frac{2\tau_{12}}{T_2}} \left[\cos\left((\omega_L^e - \omega_L^h)\tau_{12}\right) + \cos\left((\omega_L^e + \omega_L^h)\tau_{12}\right) - \right.$$
$$\left. -2\cos(\omega_L^e \tau_{12}) - 2\cos(\omega_L^h \tau_{12}) - 2\right], \tag{9}$$

$$P_{DXD}^{tr} \sim \frac{1}{4} e^{-\frac{2\tau_{12}}{T_2}} \left[\cos\left((\omega_L^e - \omega_L^h)\tau_{12}\right) + \cos\left((\omega_L^e + \omega_L^h)\tau_{12}\right) + \right.$$
$$\left. +2\cos(\omega_L^e \tau_{12}) + 2\cos(\omega_L^h \tau_{12}) - 2\right], \tag{10}$$

The theoretically obtained dependencies of exciton and trion PE signals calculated for direct and tilted polarizations on time delay are demonstrated in Fig. 2.

Theoretical analysis of the obtained dependencies for excitons (1-5) and of the similar theoretical dependencies for trions (6-10) described in Ref. [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. 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 $g_h=0$ (see expressions 4, 5, 9, 10): 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.
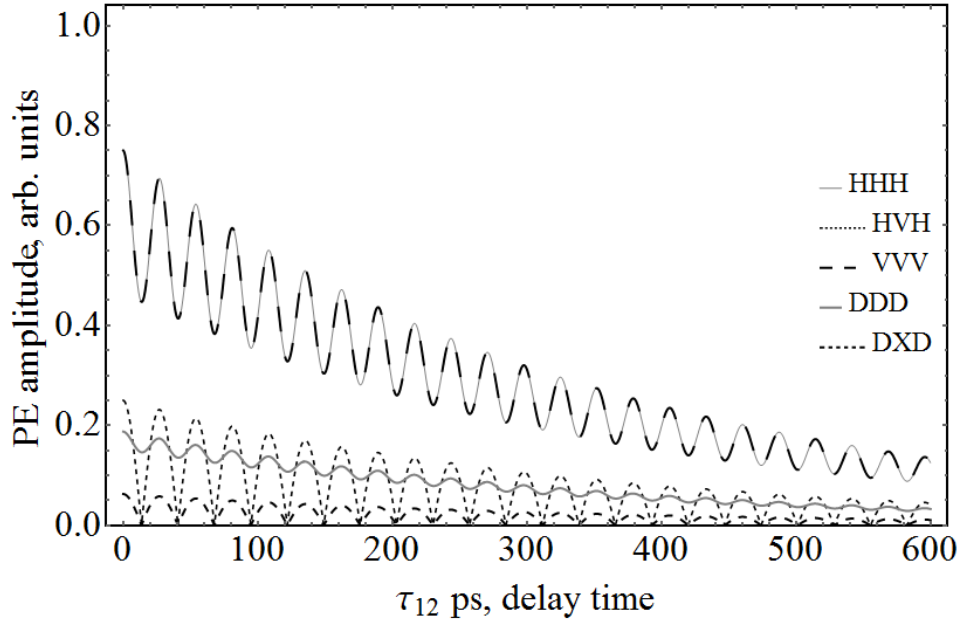
Fig. 2. Theoretically modeled PE signals for excitons and trions in direct and tilted polarization protocols. The thin gray and the black dashed overlapping lines demonstrate the PE signal in the HHH and VVV polarization geometries, the black dotted line demonstrates the PE signal in the HVH geometry, the gray solid line demonstrates PE signal in the HVH geometry, and the black short dashed line demonstrates the PE signal in DXD geometry respectively. The 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. We assume that the fraction of excitons are two times larger than trions

Finally, 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 has been analyzed.

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