Physics of the Solid State, 2023, Vol. 65, No. 1

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Manifestation of the exchange interaction of electrons separated by a potential barrier in double quantum wells in the Kerr effect

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Received September 20, 2022
Revised September 20, 2022
Accepted September 24, 2022

In tunnel-coupled quantum wells of different widths, it was found that the spin dynamics arising from resonant pulsed optical pumping of an exciton in the narrow well includes the dynamics of electron spin polarization in the wide well, although the electron level in the wide well is 55 meV lower than the electron level in the narrow well. An analysis of the obtained results showed that the observed effect is caused by the exchange interaction of spin-polarized electrons in the wide well with exciton states in the narrow well.

Keywords: semiconductor nanostructures, exchange interaction, Kerr effect.

DOI: 10.21883/PSS.2023.01.54978.478

1. Introduction

The study of the spin dynamics of a coupled system of magnetic ions and photo-excited charge carriers in magnetic nanostructures (quantum wells (QWs) and quantum dots) has attracted increased attention for many years in connection with proposals to use the magnetization of manganese ions for optical recording, storage, and processing of information [1,2]. At the same time, a number of fundamental points are far from being understood. In particular, the problem of the initial phase of the magnetization precession of manganese ions induced by short light pulses of circularly polarized light in a perpendicular magnetic field has not been completely studied. This is due to the fact that, after the pump pulse, the dynamics of the manganese magnetization is „hidden“ under a much stronger signal of the magnetization of photo-excited electrons. To eliminate the signal from electrons, we grew a structure, in which a wider (and non-magnetic) QW is placed next to the magnetic QW, into which photo-excited charge carriers rapidly drain from the magnetic (narrow) well if the barrier separating the wells is tunnel-transparent. However, recent experiments with such a structure unexpectedly demonstrated that the electron component is retained under a resonant pulsed exciton pumping in a magnetic (narrow) well [3]. In this paper, we present experimental evidence that the observed effect is due to the exchange interaction of electrons in the wide well, spin-polarized upon resonant excitation of a narrow well, with the exciton in the narrow well.

2. Samples and experimental setup

The studied structure was grown by molecular-beam epitaxy on GaAs substrate. It consists of a wide (20 nm) non-magnetic CdTe well and a narrow (8 nm) $Cd_{0.98}Mn_{0.02}Te$ magnetic well separated by a 1.6-nm thick (5 monolayers) tunnel-transparent non-magnetic $Cd_{0.88}Mg_{0.12}Te$ barrier, see Figure 1. The structure was not intentionally doped.

We measured the coherent spin dynamics with picosecond resolution using the spin Kerr effect in the pump-probe mode in a magnetic field directed perpendicular to the exciting beam (Voigt geometry). Pump and probe pulses of the same wavelength and duration of 1.5 ps were generated by a tunable Ti : Sa laser, allowing resonant excitation of ground exciton states in narrow or wide wells. The powers of the pump and probe beams are 20 mW and 5 mW, respectively. The measured Kerr rotation (KR) signals are described by the sum of exponentially decaying components of the form $A \cdot \exp(-t/\tau) \cdot \cos(\omega t + \varphi)$, where τ is the spin dephasing time, $\omega = |g|\mu_B B/\hbar$ is the Larmor frequency of spin precession in the magnetic field B, g is g-factor, φ is phase. All measurements were done at temperature $T = 6$ K.

3. Experimental results and discussion

The luminescence from the narrow well is not observed due to fast tunnelling of photo-excited carriers into a wide well. Therefore, the exciton energy levels in each of the wells were determined from the reflectance spectrum

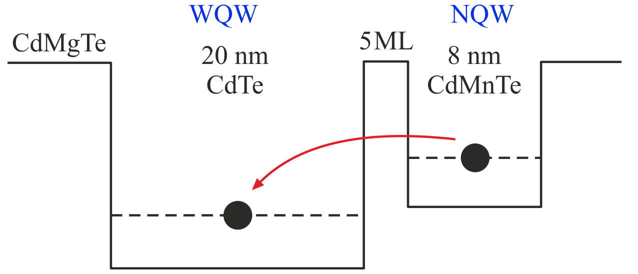

Figure 1. Schematic diagram of the studied structure electron energy levels.

of the structure (not shown here). Their values were $\lambda_X^{NQW} = 748.7\,\text{nm}$ in the narrow well and $\lambda_X^{WQW} = 775.3\,\text{nm}$ in the wide well.

Under pulsed resonant pumping of excitons in a narrow quantum well (NQW), two components are observed in the Kerr signal, fast ($\tau_1 \approx 47\,\text{ps}$) and slow ($\tau_2 \approx 700\,\text{ps}$), oscillating, respectively, with g-factors $|g_1| \approx 1.55$ and $|g_2| = 2$ and the ratio of the maximum amplitudes $A_1^{\max}/A_2^{\max} \sim 6$ (Figure 2, *a*). Since the g-factor of manganese is $g_{\text{Mn}} = 2$, it can be concluded that the slowly decaying component in the narrow well is created by the magnetization of manganese ions. The presence of a component with $|g_1| \approx 1.55$ is unexpected. First, the narrow well must be empty since the carriers photo-excited in it quickly tunnel into the wide well. Second, due to the s$-$d exchange interaction of electrons with manganese ions, the absolute value of the effective g-factor of the electron component in the magnetic well should be significantly larger, equal to ~ 30, as we found from the analysis of the reflection spectra of this structure in a longitudinal magnetic field (see also [3]).

Under resonant pumping of an exciton in a wide quantum well (WQW), three oscillating components are observed with sharply different amplitudes A and dephasing times τ (Figure 2, *b*). Among them, the first and fastest component dominates: $A_1^{\max}/A_2^{\max} \sim 100$, $A_1^{\max}/A_3^{\max} \sim 1000$ (Figure 3, *b*; the 3rd component is not shown due to the smallness), $\tau_1 \approx 45\,\text{ps}$, $\tau_2 \approx 200\,\text{ps}$, $\tau_3 \approx 800\,\text{ps}$. Moreover, the g-factors of these components are close in magnitude, $|g_1| \approx 1.56$, $|g_2| \approx 1.52$, $|g_3| \approx 1.48$, and are close to the g-factors of electrons bound into an exciton and resident electrons in a wide well [3,4].

The spectral dependences of the coherence times and g-factors of the fast (dominant) components recorded in the region of exciton resonances in the narrow and wide wells are shown in Figure 4. It can be seen that both the g-factors and the dephasing times are the same in both wells within the measurement error. This means that the electron component observed upon resonant excitation of the narrow well is generated by oscillations of the electron magnetization in the wide well.

This effect can be due to two reasons:

1) Modulation of the refractive indices for the circularly polarized components of the linearly polarized probe beam on the exciton resonance wing of the wide well (non-resonant contribution).

2) Modulation of the resonant contribution to the refractive indices of the circular components of the probe beam, caused by the exchange interaction with spin-polarized electrons in a wide well.

To establish which of the contributions is dominant, we note that the measured spectral dependence of the electron component amplitude of the Kerr signal in a narrow well (Figure 3, *a*) has a resonance behavior and manifests a change of the sign. Along with that, in the case of the degenerate (one color) pump-probe KR technique we used,

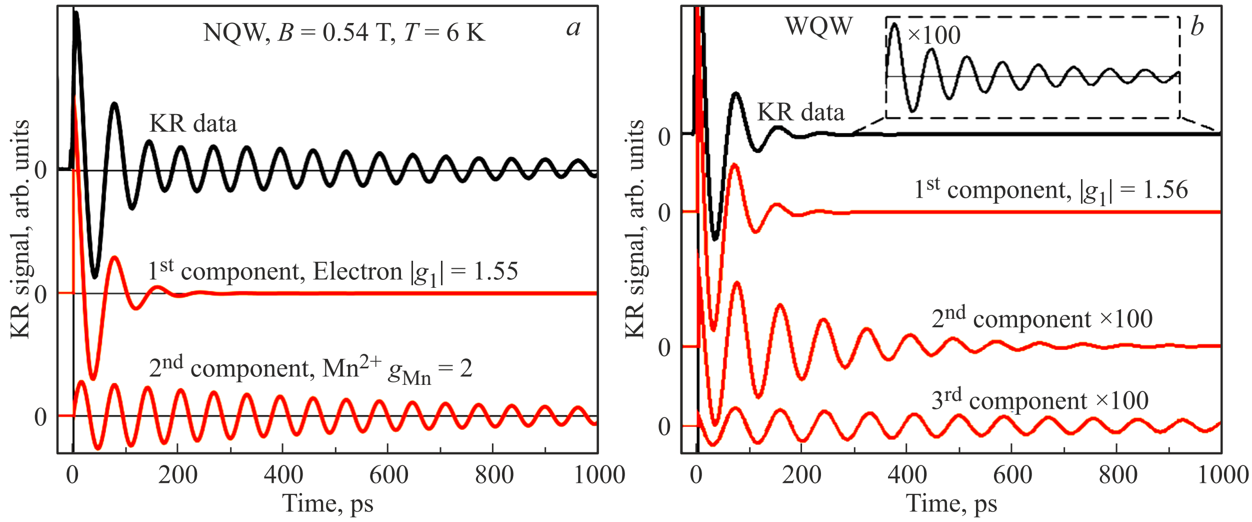

Figure 2. Kerr rotation signals (black curves) measured in transverse magnetic field $B = 0.54\,\text{T}$ in *a*) narrow and *b*) wide wells, and their approximations, respectively, by two and three components (red curves), which are shifted vertically for clarity. The pump wavelength is $\lambda_{\text{exc}}^{NQW} = 748.7\,\text{nm}$ and $\lambda_{\text{exc}}^{WQW} = 775.3\,\text{nm}$ for narrow and wide wells, respectively.

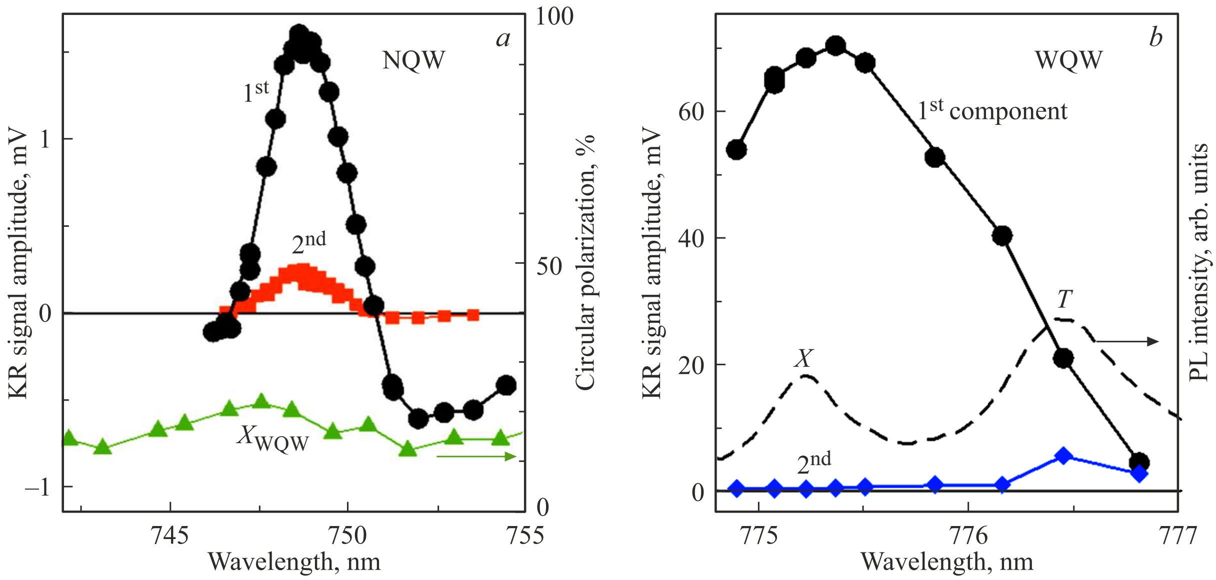

Figure 3. Spectral dependences of the amplitudes of the 1^{st} and 2^{nd} components of the Kerr signal in *a*) narrow and *b*) wide wells. The dashed curve in panel (*b*) represents the exciton (X) and trion (T) regions of the photoluminescence (PL) of a wide well measured under above-barrier excitation by a He−Ne laser. The triangles in panel (*a*) show the excitation spectrum of the PL circular polarization at the center of the WQW-exciton line measured by scanning the circularly polarized pulsed pump wavelength ($P_{\text{pump}} = 4\,\text{mW}$) in the vicinity of the NQW-exciton resonance.

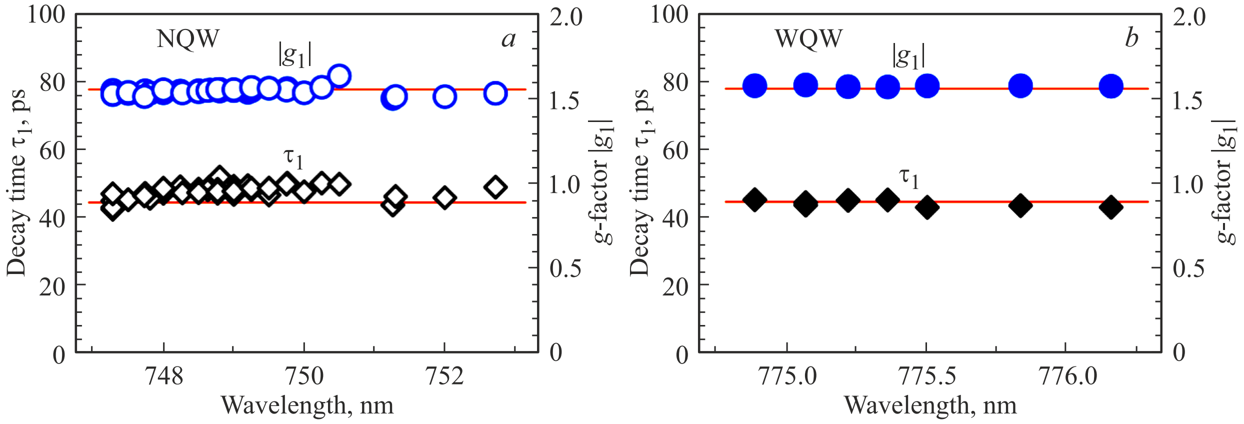

Figure 4. Spectral dependences of *g*-factors (circles) and coherence times (diamonds) of fast (first) components of Kerr signals measured in the exciton resonance region: *a*) in a narrow well (empty symbols) and *b*) in a wide well (filled symbols). Solid (red) lines are the guides for the eye.

the nature of the KR signal may depend on the shift not only of the probe beam [5], but also of the pump beam relative to the exciton level in the narrow well. We have demonstrated above that the spin polarization of electrons in the ground state of the wide well, located 55 meV below the exciton level in the narrow well, arises upon resonant pumping of an exciton in the narrow well. The spectral dependence of the electron polarization in a wide well can be found experimentally by measuring the dependence of circular polarization of an exciton line in a wide well on the wavelength of the pulsed circularly polarized pump. The excitation spectrum of the exciton circular polarization in the wide quantum well, measured with the scanning of the wavelength of the pulse pump in vicinity of the excitonic resonance of the narrow quantum well, is shown in Figure 3, *a*. It can be seen that this dependence does not change sign. This fact makes it possible to exclude the non-resonant contribution and state that the exchange interaction is the main mechanism that relates the electron spin in the ground state of the wide well and the observed rotation of the plane of linear polarization of the probe beam, which is resonant with the exciton level in the narrow well. A theoretical model of the exchange interaction, which allows describing the spectral dependences of the amplitudes of the components in Figure 3, *a*, is in progress. It will be published elsewhere.

Acknowledgments

The authors are grateful to M.M. Glazov and E.L. Ivchenko for helpful discussions.

Funding

MMD, MMA, NVK, and YGK acknowledge the support from the RFBR (project 19-52-12066) and DFG (Project B4) within the framework of the Program ICRC TRR 160, KVK thanks Saint-Petersburg State University for a research grant 73031758. The research in Poland was partially supported by the National Science Center through grant number 2018/30/M/ST3/00276.

Conflicts of interests

The authors declare that they have no conflict of interest.

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