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Spin Properties of Trions in a Dense Quasi-2D Electron Gas

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Abstract—The reflection and photoluminescence spectra of modulation-doped CdTe/CdMgTe quantum-well structures have been studied. It was found that the magnitude and sign of the Zeeman splitting of the trion reflection line depend on the electron concentration in the quantum well, whereas the magnitude and sign of the splitting of the exciton line are absolutely the same for all the electron concentrations under study. In the photoluminescence spectra, the magnitude and sign of the Zeeman splittings for the exciton and trion were the same. This "renormalization" of the trion *g* factor is explained in terms of the model of combined exciton–electron processes.

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1. INTRODUCTION

Trions in semiconductor quantum wells (QWs) have been studied for a relatively long time [1], but their nature still remains largely unclear. Particularly unusual is the behavior of trions in the presence of a rather dense 2D electron gas (2DEG). It has been found in the experimental spectra of 2DEG-containing QWs that the exciton line disappears from the spectrum even at very low electron concentrations, when the Fermi energy of the 2DEG is substantially lower than the exciton binding energy. At the same time, the trion absorption line is preserved in the spectra even at high electron concentrations, when the Fermi energy of the 2DEG exceeds the trion binding energy [2]. Moreover, even a certain narrowing of the trion absorption line with increasing electron concentration has been observed.

This looks strange because the trion binding energy is approximately an order of magnitude lower than the exciton binding energy and, seemingly, the 2DEG must primarily affect trions, rather than excitons. In addition, trions are charged quasiparticles and must be effectively scattered at electrons, in contrast to neutral electrons.

Even more unusual is the behavior of the optical spectra of excitons and trions in the presence of a magnetic field. In a magnetic field, new lines start to appear in the absorption, reflection, and fluorescence spectra of 2DEG-containing QWs. These lines linearly shift with increasing magnetic field strength. It is remarkable that there are lines that linearly shift to higher energies with increasing field strength, but there also are those that shift linearly, too, but to lower energies. In zero magnetic field, all these lines converge to the exciton absorption line, which indicates that they are directly related to the exciton. At the same time, the linear shift of the lines in a magnetic field indicates that they belong to free electrons [3, 4].

In this work, we examined the dependences of the Zeeman splitting on the electron concentration in a QW by measuring the reflection and photoluminescence (PL) spectra.

2. EXPERIMENTAL

We studied modulation-doped CdTe/$(Cd_{0.7}Mg_{0.3})Te$ QW structures containing 2DEG at various densities (from $n_e < 10^{10}$ cm^{-2} to $n_e \approx 10^{12}$ cm^{-2}). The structures included a 100-Å single QW (SQW) and were doped in barriers at a distance of 100 Å from the QW. The special design of the structures enabled control over the electron concentration, with all other parameters remaining invariable with high precision.

In this study, we compared the reflection and PL spectra measured for SQWs with various electron concentrations in magnetic fields of 0 to 11 T. Figure 1 shows the reflection spectra measured from three structures with quantum wells of different concentrations of electrons in magnetic fields from 0 to 7.4 T in two circular polarizations σ^+ (upper part of Fig. 1) and σ^- (lower part). The electron concentration was varied from $n_e < 10^9$ cm^{-2} (Fig. 1a) to $n_e = 3 \times 10^{11}$ cm^{-2} (Fig. 1d). At very low electron concentrations, the spectra show only the exciton reflection line, which experiences, with increasing magnetic field strength, a short-wavelength diamagnetic shift and Zeeman splitting. Even at a comparatively low electron concentration ($n_e = 2 \times 10^{10}$ cm^{-2}, Fig. 1b), the reflection spec-

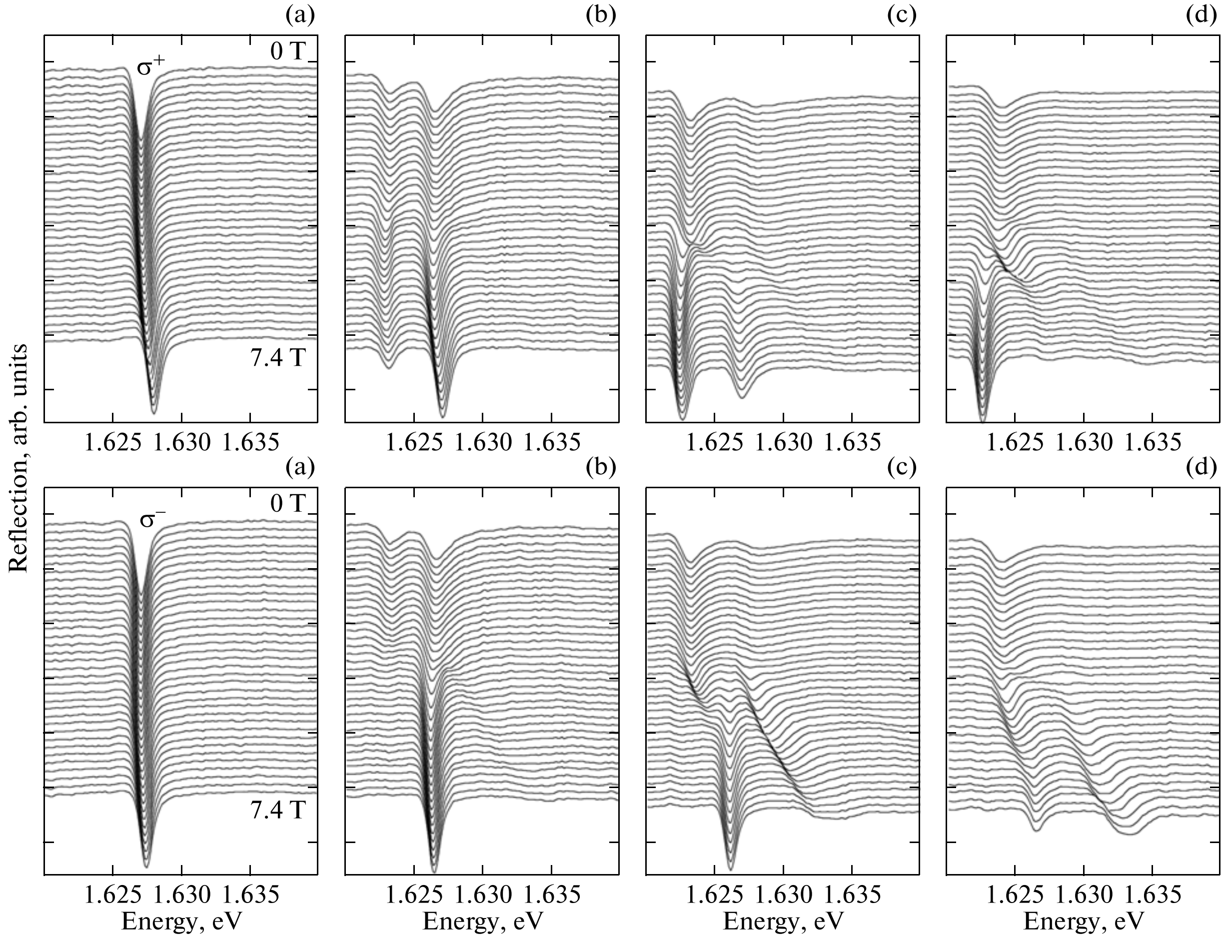

Fig. 1. Set of reflection spectra of CdTe/CdMgTe SQW structures in magnetic fields of 0 to 7.4 T in two circular polarizations: the right-hand circular component is shown in the upper part of the figure, and the left-hand circular component is shown in the lower part. The electron concentration in the well increases from left to right: (a) $<10^9$, (b) 2×10^{10}, (c) 8×10^{10}, and (d) 3×10^{11} cm^{-2}.

trum contains, together with the exciton line, a trion line. In this case, the exciton reflection line is somewhat broadened. Both lines experience Zeeman splitting and a diamagnetic shift in a magnetic field. In addition, the trion reflection line becomes strongly polarized in a magnetic field. This is due to the singlet nature of the trion ground state. As a result, a trion can be created by a photon with only a single polarization in a rather strong magnetic field. At high electron concentrations ($n_e = 8 \times 10^{10}$ cm^{-2}, Fig. 1c), the exciton reflection line almost disappears, the trion line becomes stronger, and, in addition to the trion and exciton lines, new lines, ExCR and TrCR, appear under a magnetic field. These lines were analyzed in our previous studies [3, 5]. At even higher electron concentrations ($n_e = 3 \times 10^{11}$ cm^{-2}, Fig. 1d), the exciton line completely disappears from the reflection spectrum, whereas the trion line changes only slightly.

Figure 2 shows the magnetic-field dependences of the energy positions of all lines in the spectrum for samples with different electron concentrations. It can be clearly seen that the exciton and trion lines experience an ordinary diamagnetic shift to higher energies. At the same time, the ExCR and TrCR lines shift linearly with increasing magnetic field. In addition, all the lines are split under a magnetic field. At low electron concentrations, the signs of the Zeeman splittings for the trion and exciton coincide. At high concentrations, the sign of the Zeeman splitting of the trion reflection line is opposite to the that of all other lines in the spectrum.

Figure 3 shows how the Zeeman splittings for the exciton and trion depend on the magnetic field for samples with different electron concentrations. It can be clearly seen that, at low electron concentrations, the exciton and trion splittings coincide, and with increasing electron concentration, the exciton splitting remains unchanged, whereas the trion splitting changes its magnitude and even its sign.

We also measured the PL spectra of the same samples. It was found that the sign and magnitude of the splitting of the trion line in the PL spectra exactly coincide with the splitting of the exciton PL line and are independent of the electron concentration.

This effect might be attributed to renormalization of the trion g factor in the presence of a 2DEG, but it would remain unclear as to why this effect is not

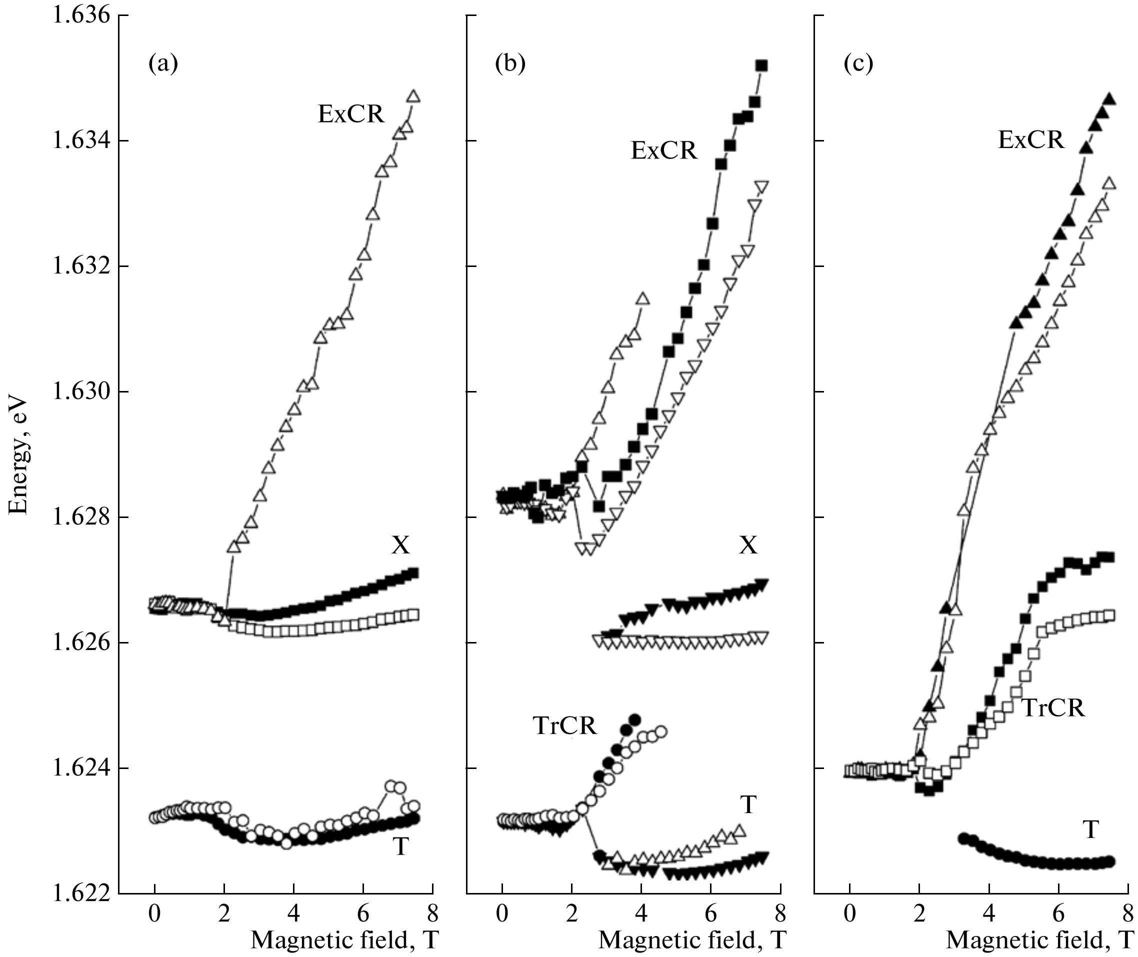

Fig. 2. Energy positions of all lines observed in the reflection spectra. Electron concentrations in the QW: (a) 2×10^{10}, (b) 8×10^{10}, and (c) 3×10^{11} cm^{-2}. X is the exciton line; T is the trion line; ExCR is the line of combined exciton-cyclotron resonance; TrCR is the line of combined trion-cyclotron resonance.

observed for the exciton, and completely unclear as to why it does not exist in the PL spectrum.

3. DISCUSSION

Let us consider in more detail the process of trion formation. The trion absorption (reflection) line is formed upon binding of a photogenerated exciton and an electron from the 2DEG. We have an electron in the initial state of this process, and a trion, in its final state. The scheme of this reaction has the following form:

$$e + \mathrm{ph} \longrightarrow \mathrm{Tr}^s. \quad (1)$$

Consequently, the energy of such a transition is given by

$$E_{\mathrm{ph}} = E_{\mathrm{Tr}} - E_e. \quad (2)$$

Because electrons in the 2DEG have energies (reckoned from the conduction-band bottom) ranging from zero to the Fermi energy: $0 \le E_e \le E_{\mathrm{F}}$, the trion absorption (reflection) line must occupy the energy range from $(E_{\mathrm{Tr}} - E_{\mathrm{F}})$ to E_{Tr}.

In a magnetic field, the initial electron occupies Landau levels below the Fermi level. When the filling factor $\nu \le 1$, the trion is formed via the binding of an electron from a lower Landau level to an exciton. The optical-transition energy upon trion formation is given by

$$E_{\mathrm{ph}} = E_{\mathrm{Tr}}(H) - \frac{\hbar\omega_c}{2}. \quad (3)$$

Because the second electron in a trion is weakly bound to the exciton, we have, in sufficiently strong magnetic fields,

$$E_{\mathrm{Tr}} \propto \frac{\hbar\omega_c}{2}. \quad (4)$$

Thus, as is the case in the experiment, the optical-transition energy upon trion formation:

$$E_{\mathrm{ph}} = \mathrm{const}. \quad (5)$$

It can be easily seen that the magnitude and sign of the Zeeman splitting of the trion absorption line exactly coincide with those for the exciton line.

At large filling factors $(2 > \nu > 1)$, two Landau levels can be partly filled by electrons. Under these conditions, the so-called trion-cyclotron resonance, TrCR, is

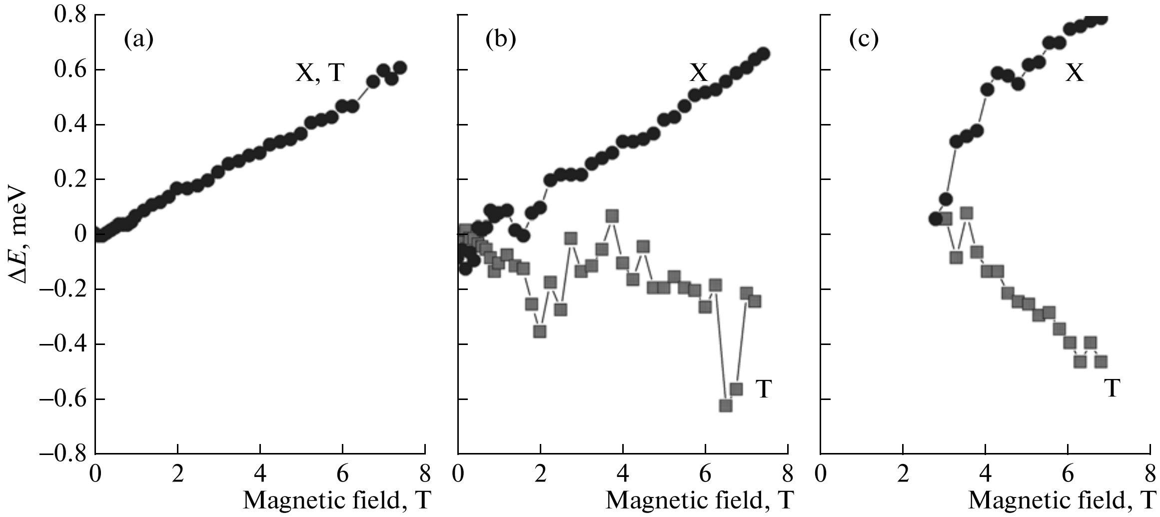

Fig. 3. Zeeman splitting (ΔE) of the exciton and trion reflection lines. The electron concentrations are the same as those in Fig. 2.

observed [5], in which an incident photon generates a trion in the singlet state and, simultaneously, induces the transition of an additional electron to one of the upper Landau levels. The corresponding reaction has the form:

$$e_1^{\uparrow} + e_1^{\uparrow} + \mathrm{ph} \longrightarrow \mathrm{Tr}^s + e_2^{\uparrow}.$$

Here, $e_1^{\uparrow}$ is an electron with spin $\uparrow$ on the lower Landau level, and $e_2^{\uparrow}$ is an electron with spin $\uparrow$ on the second Landau level. In this case, the optical-transition energy under a magnetic field is given by

$$E_{\mathrm{ph}} = E_{\mathrm{Tr}}(H) + \frac{1}{2}\hbar\omega_c. \quad (6)$$

Thus, the absorption line shifts with increasing magnetic field as $\hbar\omega_c$, upwards in energy. It is apparent that the sign and magnitude of the Zeeman splitting coincide with the sign and magnitude of the splittings for the exciton in this case as well.

Another process is also possible under these conditions, in which an incident photon gives rise to a triplet trion [6] and, simultaneously, induces the transition of an additional electron to the lower Landau level, which yields a singlet trion and an electron on the lower Landau level. This is only possible in the case of the partial filling of the higher lying Landau level, i.e., when the second Landau level is partially occupied. The scheme of this reaction has the form

$$e_1^{\uparrow} + e_2^{\uparrow} + \mathrm{ph} \longrightarrow \mathrm{Tr}^t + e_1^{\uparrow} \longrightarrow \mathrm{Tr}^s + e_2^{\downarrow}. \quad (7)$$

In this case, the optical-transition energy coincides with the energy of the singlet trion. It can be easily seen that the sign of the Zeeman splitting in this process is opposite to the those for the exciton and singlet trion.

Thus, process (7) can account for the paradoxes observed for the Zeeman splitting of a trion.

4. CONCLUSIONS

It was found in the reflection spectra of modulation-doped quantum-well structures that the magnitude and sign of the Zeeman splitting of the trion line do not coincide with the Zeeman splitting of the exciton line. The magnitude and sign of the Zeeman splitting of the trion line strongly depend on the electron concentration, whereas the Zeeman splitting for the exciton is independent of this concentration. It was also observed that the Zeeman splittings of the trion and exciton photoluminescence lines exactly coincide and are independent of the electron concentration. This phenomenon is attributed to the triplet–singlet conversion of the trion, with the simultaneous transition of an additional electron between Landau levels.

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REFERENCES

1. K. Kheng, R. T. Cox, et al., Phys. Rev. Lett. **71**, 1752 (1993); A. J. Shields, M. Pepper, et al., Phys. Rev. B **52**, 7841 (1995); G. Finkelstein, H. Shtrinkman, and I. Bar-Joseph, Phys. Rev. B **53**, 1709 (1996).
2. G. V. Astakhov, V. P. Kochereshko, D. R. Yakovlev, W. Ossau, J. Nürnberger, W. Faschinger, and G. Landwehr, Phys. Rev. B **62**, 10345 (2000).
3. D. R. Yakovlev, V. P. Kochereshko, et al., Phys. Rev. Lett. **79**, 3974 (1997).
4. K. J. Nash, M. S. Skolnick, M. K. Saker, and S. J. Bass, Phys. Rev. Lett. **70**, 3115 (1993).
5. V. P. Kochereshko, G. V. Astakhov, D. R. Yakovlev, W. Ossau, G. Landwehr, W. Faschinger, T. Wojtowicz, G. Karczewski, and J. Kossut, Physica E **17**, 197 (2003).
6. D. Andronikov, V. Kochereshko, et al., Phys. Rev. B **71**, 165339 (2005).

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