Anomalous behavior of the indirect excitons in (Cd,Mn)Te/(Cd,Mg)Te/CdTe double QW structures

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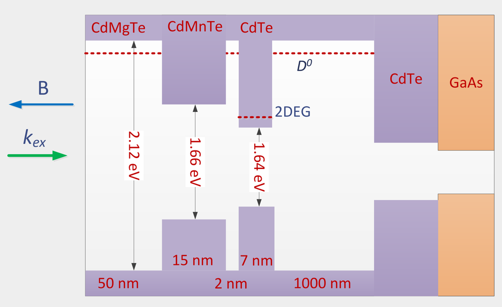
Motivation

In recent decades, the properties of coupled double quantum wells (DQWs) and dots have been widely studied, including Bose-Einstein condensation (BEC) in DQWs [1,2], magnetic polaron states [3], and spectra of double quantum dots [4]. Although the probability of indirect optical transitions is about two or more orders of magnitude lower than that of direct transitions, a long lifetime of indirect excitons (>10-8 s) allows their accumulation in the structures. Lastly, it allows us to observe their PL spectra when the energy of the indirect excitons is lower than that of the direct ones. It should be noted that the predominant part of the experimental studies has been carried out in the presence of an electric field providing the necessary shifts of the positions of the carrier states in the QWs. As a result, in the electric field, one of the possible indirect excitons becomes the lowest exciton state in the system. For DQW structures where one of the wells is semimagnetic, tuning of the indirect excitons (IX) energy can be achieved by applying a magnetic field due to the effect of giant spin splitting (GSS) [4, 5].The spin splitting of the exciton states in the DMS well or in the well bordering to the DMS barrier can then reach several tens of meV in the available magnetic fields. Only the lowest of the spin-splitting exciton states seems to be populated at low temperatures. Varying the applied magnetic field makes it possible to change the energy of this state. An important feature of DQW (o experiments with exciton energies driven by the magnetic field is the absence of electrical coupling via contacts and external circuitry between wells contained in the structure. At the same time, the unbound carriers generated in the structure under optical excitation can generate different electric charges in the wells and thus a potential difference between the wells, depending on the excitation conditions. This can affect the energy of the indirect excitons in addition to the effect of the applied magnetic field.

To the best of our knowledge, the phenomenon described above has not been observed. In this paper we describe the results of studies of CdMnTe/CdTe double quantum wells separated by a thin barrier, which is tunnel-transparent at least for conduction electrons. In our experiments we found a dependence of the indirect exciton energy on the energy of the optical excitation quanta. This effect may be due to the influence of the inter-well charge generated by optical excitation on the structure of the electronic levels in the DQW.

Samples and experimental details



MBE grown double quantum well structure $Cd_{0.95}Mn_{0.5}Te$/ CdTe/$Cd_{0.8}Mg_{0.2}Te$.

- CdMgTe barrier width — 1.9 nm
- Spacer width—1000 nm
- CdMnTe QW width—15 nm
- CdTe QW width 6.9 nm

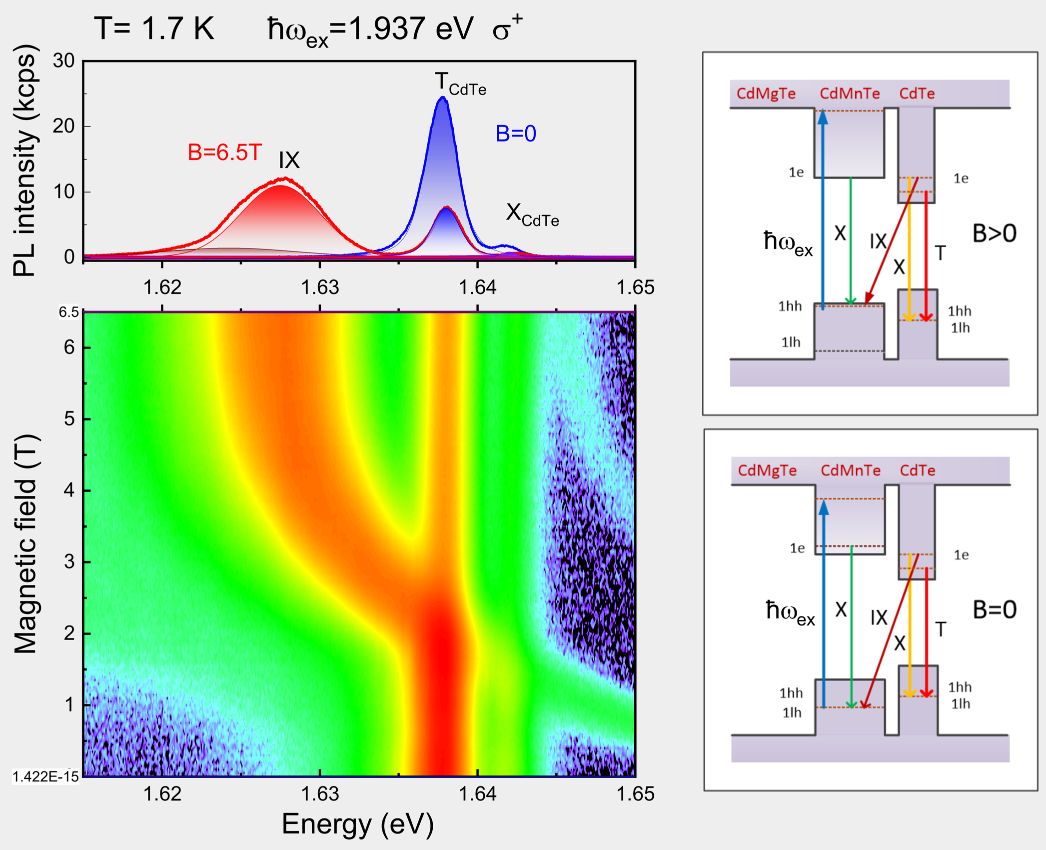
Steady-state and time-resolved PL spectra of exciton emission from DQW were studied at magnetic fields up to B=7 T in Faraday geometry (B ‖ k ‖ z).

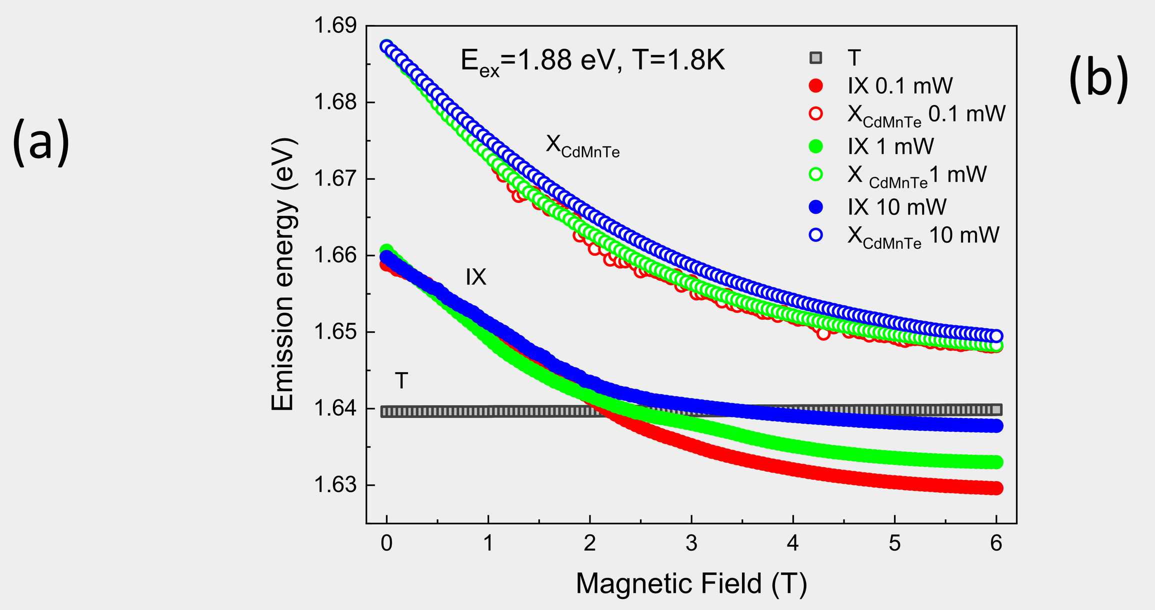
The dynamics of PL were measured with a time resolution of 100 ps.

PLE spectra were measured using a EQ-99 laser-driven light source combined with a 0.3 m monochromator.

The experiments were performed at temperatures below T=1.9 K.

Magnetic field tuning of excitons levels in CdMnTe/CdTe/CdMgTe DQW: "red" shift of IX due to GSS effect

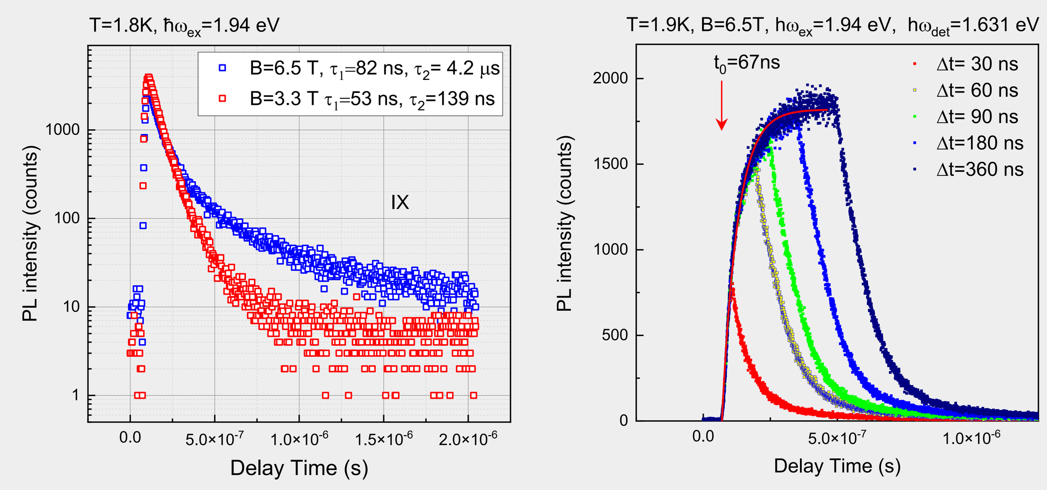




(a) -Magnetic field dependence of exciton emission from CdMnTe/CdTe/CdMgTe DQW (3D colour plot) and excitons radiative transition diagrams without and with applied magnetic field.

(b) -Dependence of the energy of the exciton radiative transition on the magnetic field at different power of "under-barrier" excitation

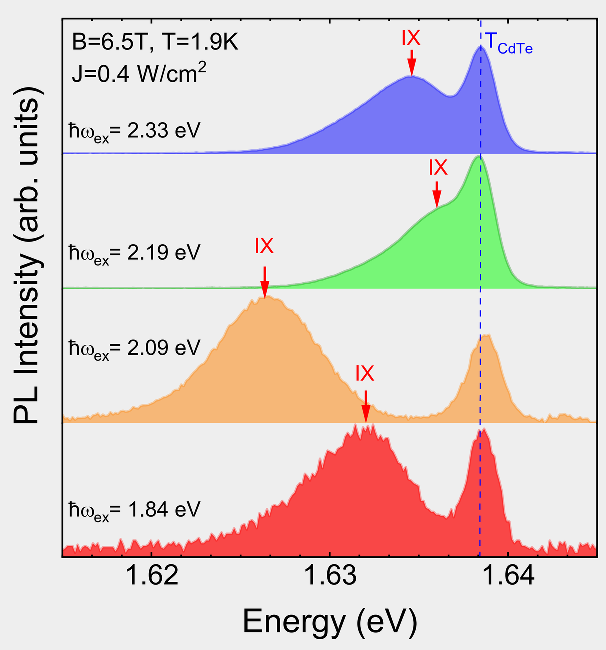
PL dynamics of indirect excitons



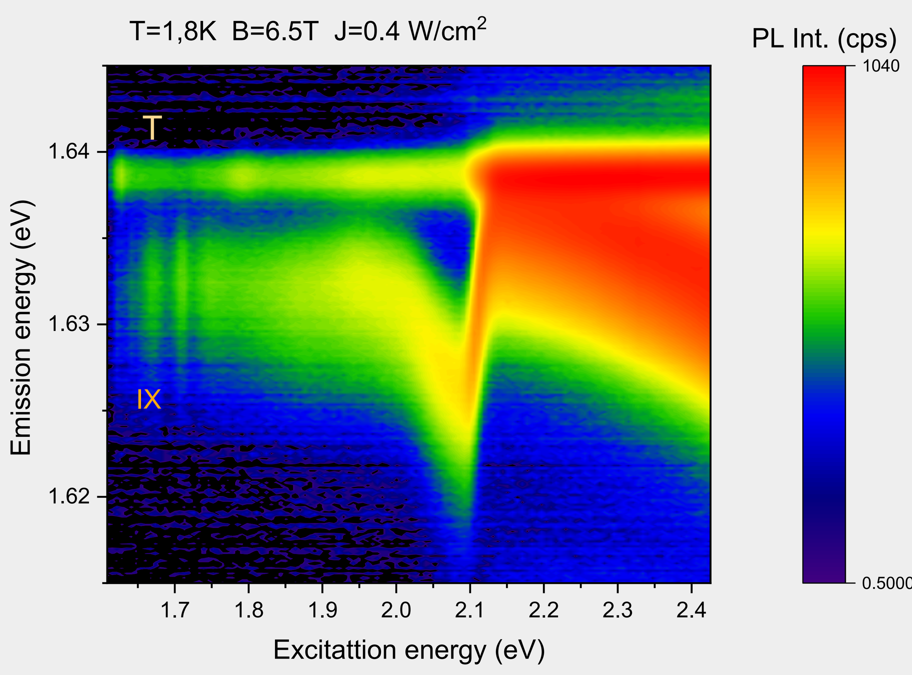
The emission and decay of the PL line of indirect excitons under the condition of their excitation by pulses of different duration. Under-barrier excitation was used.

It is possible to see long times of ignition and delay of IX PL emission. This is a result of the low radiative transition probability for IX excitons and their accumulation before radiative recombination. It supports that we are really dealing with indirect excitons.

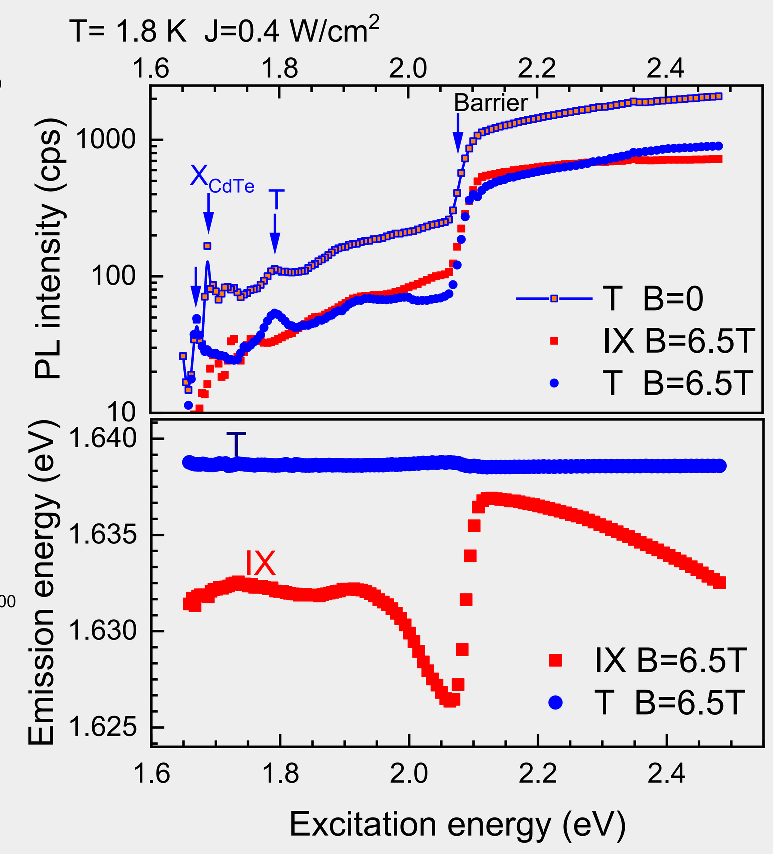
Dependence of indirect exciton (IX) energy on the energy of excitation



PL spectra of DQW at different excitation energies.



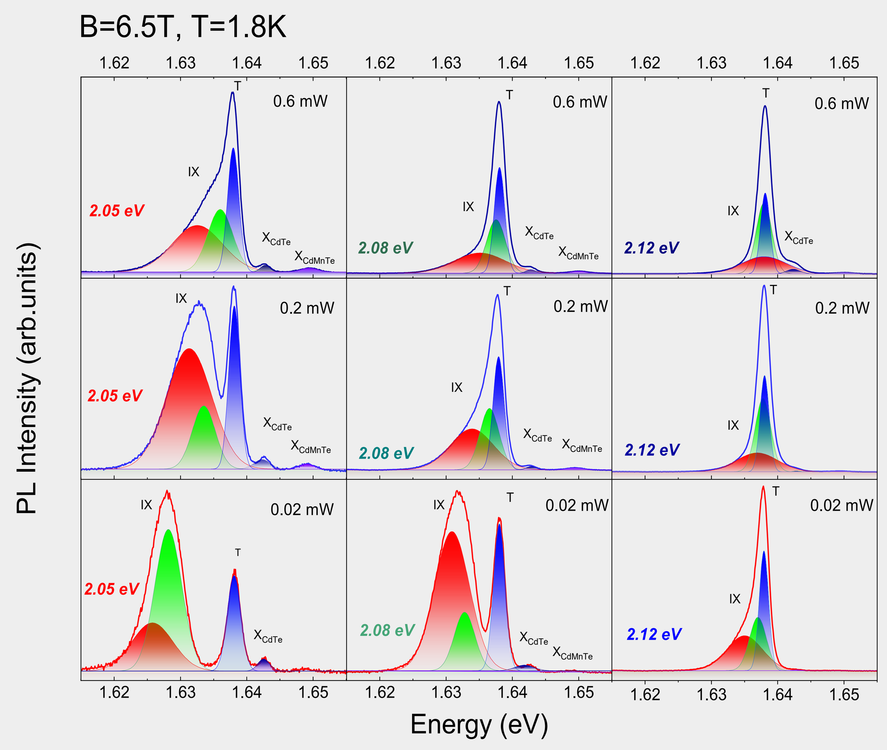
PLE spectra of the CdMnTe/CdTe/CdMgTe DQW as a 3D color plot



PLE spectra of indirect exciton and trion at B=0 and B=6.5T and dependences of energies of indirect exciton and trion on excitation energy at B=6.5T

It was unexpected that the energy of indirect exciton emission (IX) is significantly dependent on the excitation energy. The energy of IX depends non-monotonically on the excitation energy and varies more than 15 meV. A jump of the IX energy behaviour is observed in the vicinity of a DQW barrier energy. At the same time, the energy of trion and direct excitons does not depend on the excitation energy. To the best of our knowledge, such behaviour of indirect excitons has not previously been observed for spatially quantized systems.

Behaviour of excitons emission in DQW structure on the excitation energy and power



PL spectra of CdMnTe/CdTe/CdMgTe DQW at different excitation energies and powers. The excitation energy varied around the barrier energy (from 2.05 to 2.12 eV). The excitation power varied from 0.02 mW to 0.6 mW. Increasing the excitation power and energy leads to vanishing of the "red" shift of the indirect exciton

Discussion

Anomalous non-monotonic behaviour of the IX emission spectrum is observed near the energy of a (Cd,Mg)Te barrier band edge, while direct trions (T) and excitons do not depend on the optical excitation energy. The energy difference between IX and T, i.e. the magnitude of the effect, depends on the optical excitation power density. We suggest that the main mechanism responsible for this effect is due to the accumulation of photo-induced carriers in different QWs, which induces the appearance of an intrinsic electrostatic field that strongly modifies the energy spectrum of IX. The effect is also driven by the spin temperature of the carriers localized in the (Cd,Mn)Te QW, which determines its strong nonlinearity.

Summary

- In the CdMnTe/CdTe/CdMgTe DQW, indirect excitons formed by a 1e electron in the non-magnetic CdTe QW and a 1hh hole in the CdMnTe QW have been observed. In a magnetic field B> 2T the indirect exciton becomes the lowest allowed state.
- The indirect exciton is characterised by a significant lifetime exceeding 100 ns depending on the magnetic field.
- The effect of the dependence of the indirect exciton energy on the photoexcitation energy was found for the first time. This dependence is non-monotonic and the magnitude of the effect depends on the excitation energy.
- The observed phenomenon is due to the thermalisation processes of nonequilibrium holes in CdMnTe magnetic QWs, the inter-well charge relaxation processes and the hybridisation dynamics of excitons and carriers in the wells.
- The results obtained can be applied to the study of BEC in semiconductor nanostructures.

Refernces:

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