Conference materials
UDC 538.935
DOI: https://doi.org/10.18721/JPM.161.108

Photoluminescence and energy transfer between CdTe/CdMnTe quantum wells separated by thick barriers

V.F. Agekyan [1], N.G. Filosofov [1]✉, G. Karczewski [2], A.N. Resnitsky [3],
A.Yu. Serov [1], A.S. Smirnov [3], I.V. Shtrom [1], S.Yu. Verbin [1]

[1] St. Petersburg State University, St. Petersburg, Russia;
[2] Institute of Physics PAN, Warsaw, Poland;
[3] Ioffe Institute, St. Petersburg, Russia
✉ n.filosofov@spbu.ru

Abstract. Reflection, luminescence (PL), and luminescence excitation (PLE) spectra of a CdTe/CdMnTe heterostructure with quantum wells of different thicknesses are studied. It has been found that at low temperatures light emission comes from localized exciton states of quantum wells. The PLE spectra show that the contributions of excitons and free carriers to the population of quantum well depend on its thickness. The ratio of these contributions affects the dependence of the quantum well luminescence intensity on the level of optical excitation. It has been established that the coupling of quantum wells, separated by thick barrier layers, occurs through exciton excited states.

Keywords: exciton, heterostructures, coupling quantum wells

Funding: Grant No. 75746688 (V. Agekyan, A. Serov, and N. Filosofov) of St. Petersburg SU and UMO-2021/41/B/ST3/03651 (G. Karczewski).

Citation: Agekyan V.F., Filosofov N.G., Karczewski G., Resnitsky A.N., Serov A.Yu., Smirnov A.S., Shtrom I.V., Verbin S.Yu., Photoluminescence and energy transfer between CdTe/CdMnTe quantum wells separated by thick barriers, St. Petersburg State Polytechnical University Journal: Physics and Mathematics. 16 (1.1) (2023) 49–53. DOI: https://doi.org/10.18721/JPM.161.108

Материалы конференции
УДК 538.935
DOI: https://doi.org/10.18721/JPM.161.108

Фотолюминесценция и перенос энергии между квантовыми ямами CdTe/CdMnTe, разделенными широкими барьерами

В.Ф. Агекян [1], Н.Г. Философов [1]✉, Г. Карчевский [2], А.Н. Резницкий [3],
А.Ю. Серов [1], А.С. Смирнов [3], И.В. Штром [1], С.Ю. Вербин [1]

[1] Санкт-Петербургский государственный университет, Санкт-Петербург, Россия;
[2] Институт физики ПАН, г. Варшава, Польша;
[3] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ n.filosofov@spbu.ru

Аннотация. Исследованы спектры отражения, люминесценции (PL) и спектры возбуждения люминесценции (PLE) гетероструктур CdTe/CdMnTe, содержащих квантовые ямы различной толщины. Было обнаружено, что низкотемпературная люминесценция обусловлена локализованными состояниями экситона в квантовой яме. Анализ PLE позволяет сделать вывод, что вклад экситонов и свободных носителей в заселение состояний квантовой ямы зависит от ее толщины. Показано, что соотношение этих вкладов в интенсивность люминесценции локализованного экситона квантовой ямы зависит от уровня оптического возбуждения. Установлено, что квантовые ямы, разделенные широким барьером, взаимодействуют друг с другом посредством возбужденных состояний экситона.

Ключевые слова: экситон, гетероструктуры, связанные квантовые ямы

Финансирование: Грант № 75746688 (В. Агекян, А. Серов и Н. Философов) СПбГУ и UMO-2021/41/B/ST3/03651 (Г. Карчевский).

Ссылка при цитировании: Агекян В.Ф., Философов Н.Г., Карчевский Г., Резницкий А.Н., Серов А.Ю., Смирнов А.С., Штром И.В., Вербин С.Ю., Фотолюминесценция и перенос энергии между квантовыми ямами CdTe/CdMnTe, разделенными широкими барьерами // Научно-технические ведомости СПбГПУ: Физико математические науки. 2023. Т. 16. № 1.1. С. 49–53. DOI: https://doi.org/10.18721/JPM.161.108

Introduction

The energy transfer process between quantum wells separated by barriers is of fundamental interest in semiconductor physics. One might expect that the quantum wells separated by a thick barrier would be independent at low temperature, because the energy transfer is inefficient by both tunneling and thermal excitation. In this paper, however, we present quantum well luminescence results that show evidence of efficient energy transfer between wells separated by thick (20 nm) barrier at low temperature.

Materials and Methods

We have studied reflection, photoluminescence (PL) and photoluminescence excitation (PLE) spectra of a $CdTe/Cd_{1-x}Mn_xTe$ heterostructure, containing three CdTe quantum wells (QWs) 16, 8, and 4 monolayers (ML) thick (QW-1, QW-2, and QW-3, respectively), separated by 62 ML thick $Cd_{1-x}Mn_xTe$ barrier layers (Fig. 1). The heterostructure is grown on GaAs-CdTe substrate, the QW-1 is separated from the substrate by a $Cd_{1-x}Mn_xTe$ layer 150 ML thick, the $Cd_{1-x}Mn_xTe$ cap layer have a thickness of 62 ML. A nominal value of x is 0.45, and 1 ML thicknesses are 0.324 and 0.320 nm for CdTe and $Cd_{0.55}Mn_{0.45}Te$, respectively.

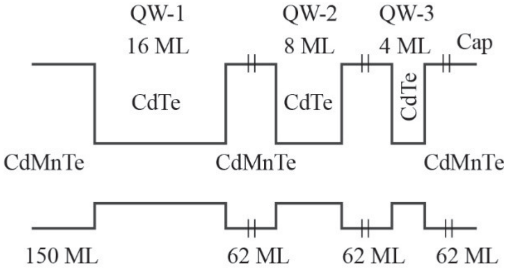

Fig. 1. Energy profile scheme of the $CdTe/Cd_{1-x}Mn_xTe$ heterostructure with three quantum wells QW-1, QW-2, and QW-3

The He-Cd laser with 442 nm wavelength was used to excite a photoluminescence. The samples were placed in the closed-cycle He cryostat, and the spectrometer MDR-204 and photoelectron multiplier Hamamatsu R928 were used to record the low-temperature PL spectra. Micro-PL spectra were excited with Nd-YAG laser (λ_{exc} = 532 nm) and recorded using the optical complex based on spectrometer LabRAM HR Evolution (Horiba, France) equipped with a confocal microscope.

Results and Discussions

Under above barrier excitation three emission bands of QW-1, QW-2, and QW-3 are observed in the PL spectrum (Fig. 2), the QW-3 band overlaps with a broad band of Mn^{2+} intracenter luminescence. The FWHM of QW bands are 4.5, 10, and 45 meV, respectively, which is in agreement with the estimates of the inhomogeneous broadening of exciton levels due to one ML fluctuations of the QW thicknesses [1, 2].

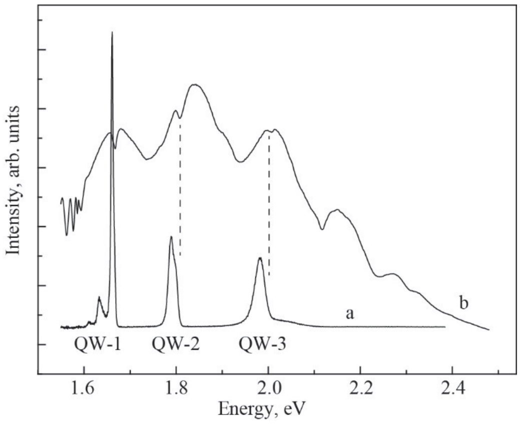

Fig. 2. Photoluminescence (*a*) and reflection (*b*) spectra of the CdTe/$Cd_{1-x}Mn_xTe$ heterostructure at $T = 5$ K. The dashed lines show the features of the reflection spectrum, corresponding to the energies of free excitons (FE) of quantum wells

In the reflection spectrum against the background of interference fringes, features are observed, their energies corresponding to the energy levels of free excitons (FE) of three QWs (Fig. 2). At $T = 5$ K the maxima of QW bands are shifted towards low energy relative to the features of the reflection spectrum. This suggests that luminescence comes mainly from localized exciton states (LE) at low temperatures.

As the excitation level increases, the low-energy component of the doublet saturates, while the high-energy component relatively enhances (Fig. 3). This makes it possible to interpret these components as LE and free exciton (FE) emission, respectively. As the temperature increases, the LE component weakens, while the FE component increases, which confirms their origin (Fig. 4). In the QW-2 spectrum the doublet structure appears to be less distinct, in QW-3 spectrum it is not resolved at all. However, the temperature behavior of FWHM and maximum energy position of QW-3 PL band (Fig. 5) indicate the redistribution of the light emission intensity in favor of FE, when the sample is heated [3].

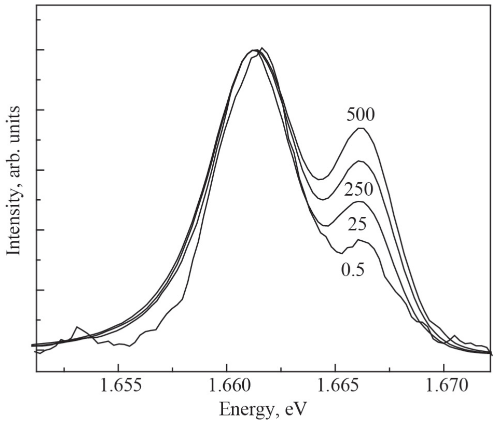

Fig. 3. QW-1 PL spectra at different excitation levels (from 0.5 up to $5{\cdot}10^2$ W/cm^2). The spectra are normalized to the maximum

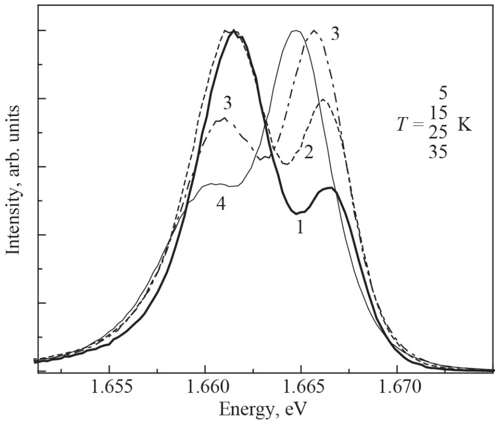

Fig. 4. Spectra of QW-1 PL at various temperatures (free FE and localized LE excitons). The spectra are normalized to the maximum

An anomalous dependence of QW-1 PL on the excitation level was revealed (Fig. 6). At an excitation level of less than 1 W/cm^2 the QW-1 PL band practically does not stand out distinctly against the noise. However, at an excitation level of more than 100 W/cm^2 the intensity of QW-1 PL band already exceeds the intensities of QW-2 and QW-3 PL. Such behavior of the QW-1 PL can be explained by the presence of a non-radiative channel near QW-1, which saturates as the excitation increases. In the heterostructure under study QW-1 is significantly removed from the substrate and the surface, so the actual non-radiative centers are most likely located at the QW-1 interfaces.

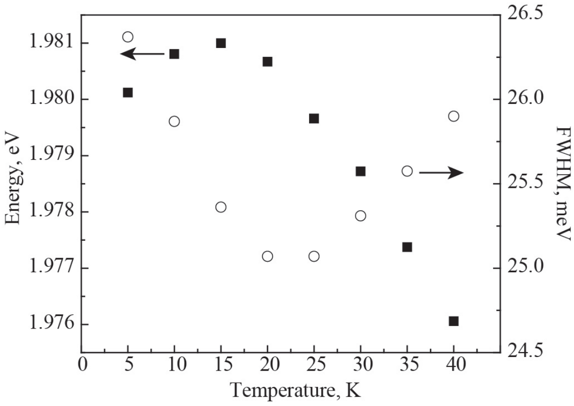

Fig. 5. Temperature dependences of FWHM and maximum energy of the QW-3 PL band

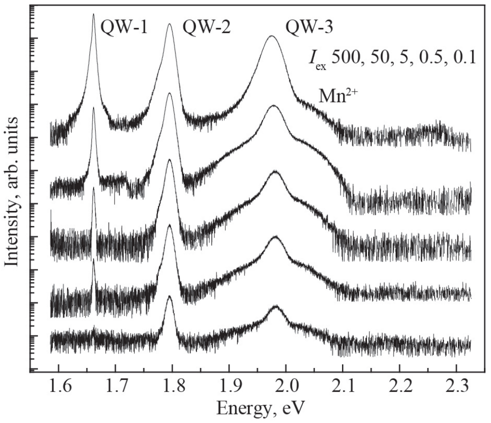

Fig. 6. PL spectra (shifted for clarity) of the $\mathrm{CdTe/Cd_{1-x}Mn_xTe}$ heterostructure at different excitation levels from 0.1 up to 5·10^2 W/cm^2 (lowest to uppest spectra, respectively), $T = 10$ K

The question arises, why non-radiative centers affect QW-1 PL much stronger as compared to QW-2 and QW-3. The answer is provided by the study of the PLE spectra in the above-barrier region. As can be seen from Figure 7, in this spectral region the PLE QW-2 and QW-3 spectra have a distinct maximum at the region of 2.34 eV, which corresponds to the exciton states of the barrier. At the same time, in the PLE QW-1 spectrum the exciton maximum in this region is completely blurred and “the center of gravity” of the PLE spectrum is noticeably shifted to the short-wave region. This result means that the QW-1 states are filled mainly with free carriers, while the filling of the QW-2 and QW 3 states dominates by the exciton mechanism. Under weak excitation a carrier captured in QW-1, can relax to non-radiative center without waiting for a carrier of the opposite sign [4, 5]. When the exciton is captured, its relaxation as a whole to a non-radiative center is less probable. Moreover, the relaxation is limited by the fast exciton radiative recombination. In addition, it should be also taken into account that the higher mobility of carriers in thick QW increases the probability of their capture by the non-radiative centers.

Thus, the PLE spectra indicate that the narrower is the QW, the less efficiently it is filled through the free carrier mechanism. The reason may be a weak localization of carriers, the holes especially, in the narrow QWs. The exciton localization turns out to be more efficient, since the electron holds the hole with its Coulomb field.

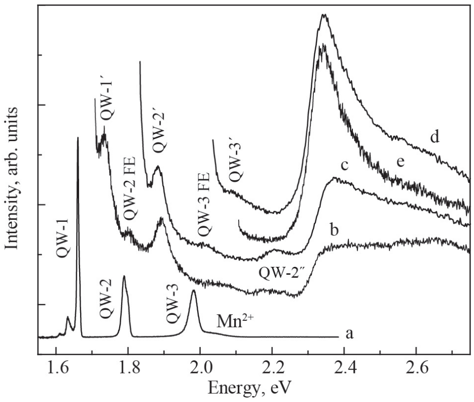

Fig. 7. PL spectrum (*a*) and PLE spectra of QW-1 (*b*), QW-2 (*c*), QW-3 (*d*) and Mn^{2+} (e), $T = 5$ K

Additional information, concerning to the interaction of QWs, is provided by the PLE spectra in the below-barrier region. The structure of the PLE spectra suggests that the QW-1, QW-2, and QW-3 are coupled to each other. Indeed, the QW-2 PLE spectrum has a maximum at 2.020 eV, coinciding with the energy of the QW-3 excited state; the QW-1 PLE maximum at 1.891 eV coincides with the QW-2 FE excited state, the weaker maximum at 1.810 eV corresponds to the QW-2 FE ground state (Fig.7).

It should be also seen from Figure 7 that the transfer of the above-barrier excitation to Mn^{2+} $3d$-shell occurs through the exciton mechanism, so that the shape of the PLE spectrum of manganese intracenter luminescence makes it possible to refine the exciton energy of $Cd_{1-x}Mn_xTe$ barriers. The maximum at 2.34 eV of PLE spectrum of manganese intracenter luminescence corresponds to the FE position in $Cd_{1-x}Mn_xTe$ for $x = 0.47$ [6], which is close to the nominal of $x = 0.45$.

Conclusion

The features, corresponding to the ground and excited exciton states, were found in the PLE spectra of all QW, studied in this work. We can conclude that in the case of QWs, separated by thick barriers, when there is no connection between the ground states of QWs, energy transfer may occur through the excited states.

Acknowledgments

The spectra, shown in Figure 6, were excited with Nd-YAG laser ($\lambda_{exc} = 532$ nm) and recorded using an optical complex, based on spectrometer LabRAM HR Evolution (Horiba, France), equipped with a confocal microscope.

REFERENCES

1. **Waag A., Schmeusser S., Bicknell-Tassius R.N., Yakovlev D.R., Ossau W., Landwehr G.,** Molecular beam epitaxial growth of ultrathin CdTe-CdMnTe quantum wells and their characterization, Appl. Phys. Lett. 59(23) (1991) 2995–2997.

2. **Kutrowski M., Kopalko K., Karczewski G., Wojtowicz T., Kossut J.,** Luminescence study of CdTe/$Cd_{1-x}Mn_xTe$ quantum wells, grown by MBE, Thin Solid Films. 26 7(1–2) (1995) 64–68.

3. **Klochikhin A., Reznitsky A., Dal Don B., Priller H., Kalt H., Klingshirn C., Permogorov S., Ivanov S.,** Temperature dependence of photoluminescence bands in $Zn_{1-x}Cd_xSe$/ZnSe quantum wells with planar CdSe islands, Phys. Rev. B. 69 (8) (2004) 085308.

4. **Budkin G.V., Eremenko M.V., Reznitsky A.N.,** Charge and energy transfer in double asymmetric quantum wells with quantum dots, J. Exp. Theor. Physics. 124 (5) (2017) 740.

5. **Agekyan V., Filosofov N., Karczewski G., Serov A.Yu., Shtrom I., Reznitsky A.,** Spectroscopic evidence of tunnel coupling between CdTe quantum wells in the CdTe/ZnTe heterostructures, J. Phys. Conf. Ser. 2103 (1) (2021) 012102.

6. **Goede O., Heimbrodt W.,** Optical properties of (Zn, Mn) and (Cd, Mn) chalcogenide mixed crystals and superlattices, PSS(b). 146 (1) (1988) 11–62.

THE AUTHORS

AGEKYAN Vadim
v.agekyan@spbu.ru
ORCID 0000-0002-5508-6660

FILOSOFOV Nikolai
n.filosofov@spbu.ru
ORCID 0000-0001-6004-3553

KARCZEWSKI Grzegorz
carcz@ifpan.edu.pl
ORCID 0000-0003-3441-1425

RESNITSKY Alexander
alexander.reznitsky@mail.ioffe.ru
ORCID 0000-0001-7876-4279

SEROV Alexey
a.serov@spbu.ru
ORCID 0000-0003-1122-9014

SMIRNOV Alexander
Alex.Smirnov@mail.ioffe.ru
ORCID 0000-0001-9709-5138

SHTROM Igor
i.shtrom@spbu.ru
ORCID 0000-0001-8912-2570

VERBIN Sergey
s.verbin@spbu.ru
ORCID 0000-0001-5791-7707

Received 11.10.2022. Approved after reviewing 15.11.2022. Accepted 15.11.2022.